Experimental Overview of Drell-Yan Process

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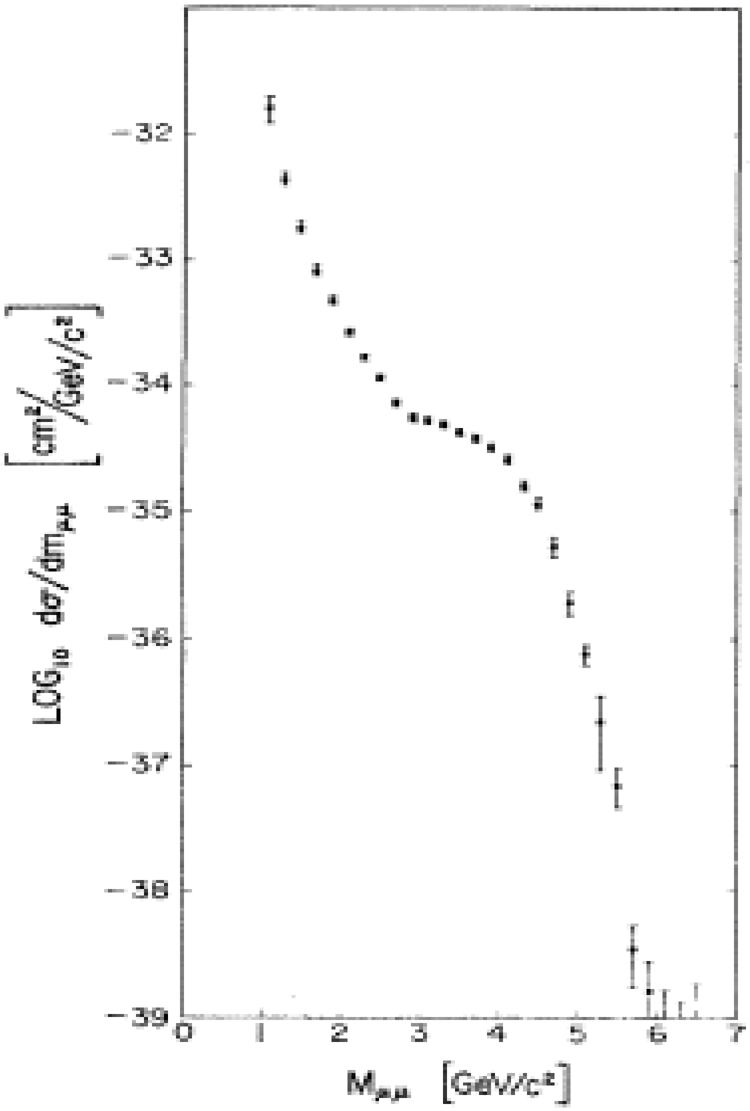
ECT* Workshop on “Drell-Yan and Hadron Structure”
Trento, May 21-25, 2012

Outline

- Brief history of Drell-Yan experiments
- Results from Fermilab Drell-Yan experiments
- What are the remaining puzzles and crucial future experiments?

First Dimuon Experiment

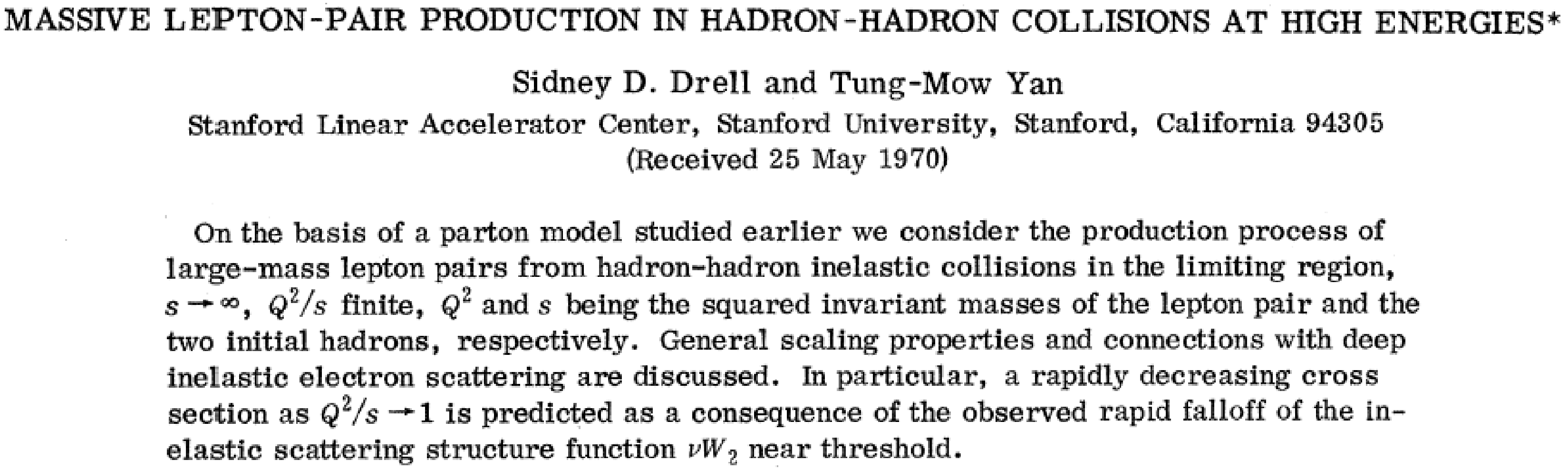


$p + U \rightarrow \mu^{+} + \mu^{-} + X$ 29 GeV proton

Lederman et al. PRL 25 (1970) 1523

- Experiment originally designed to search for intermediate weak boson
- Missed the J/Ψ signal !
- "Discovered" the Drell-Yan process

The Drell-Yan Process



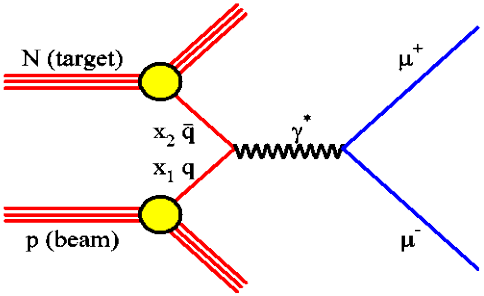
MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

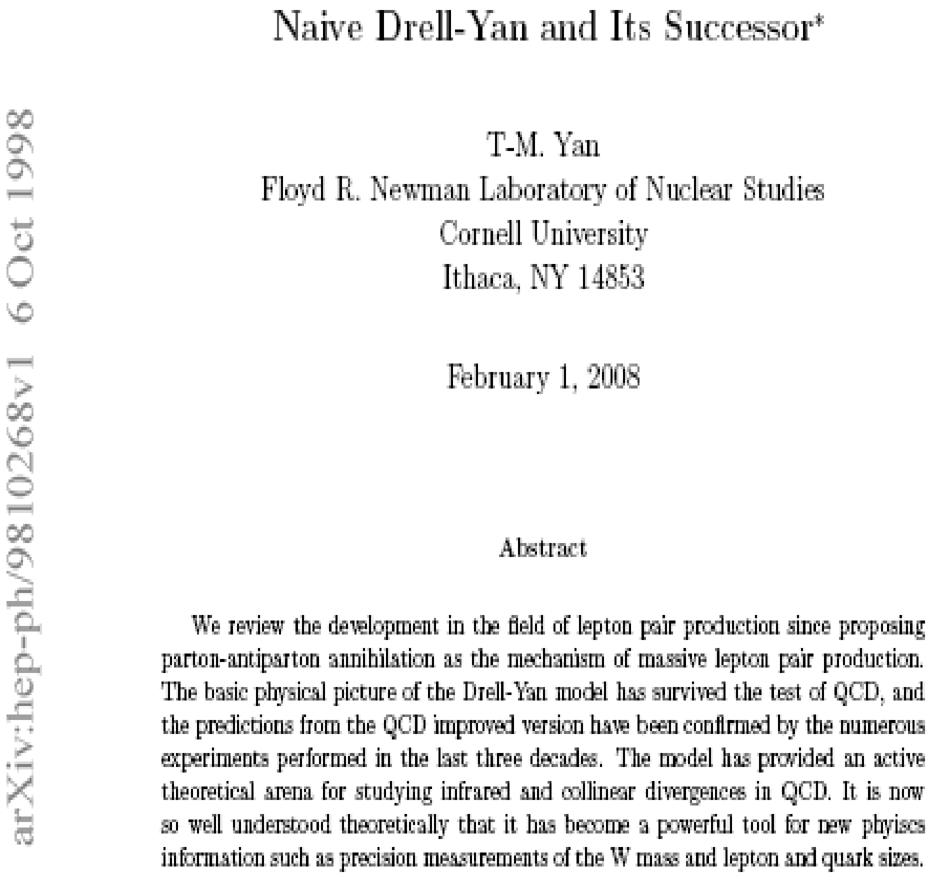
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

The Drell-Yan Process: $pN \to \mu^+\mu^- X$



$$\left(\frac{d^2\sigma}{dx_1dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$



Naive Drell-Yan and Its Successor*

T-M. Yan
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Cornell University
Ithaca, NY 14853

February 1, 2008

Abstract

We review the development in the field of lepton pair production since proposing parton-antiparton annihilation as the mechanism of massive lepton pair production. The basic physical picture of the Drell-Yan model has survived the test of QCD, and the predictions from the QCD improved version have been confirmed by the numerous experiments performed in the last three decades. The model has provided an active theoretical arena for studying infrared and collinear divergences in QCD. It is now so well understood theoretically that it has become a powerful tool for new phyiscs information such as precision measurements of the W mass and lepton and quark sizes.

- "… our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity…"
- "… the successor of the naïve model, the QCD improved version, has been confirmed by the experiments…"
- "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics."

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*Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement.

Success and difficulties of the “naïve” Drell-Yan

(From Yan’s 1998 article)

Success:

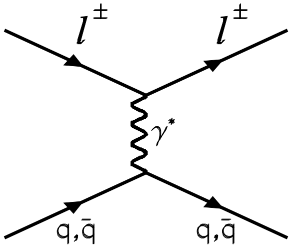
- Scaling of the cross sections (depends on x_1 and x_2 only)
- Nuclear dependence (cross section depends linearly on the mass A)
- Angular distributions ($1+\cos^2\Theta$ distributions)

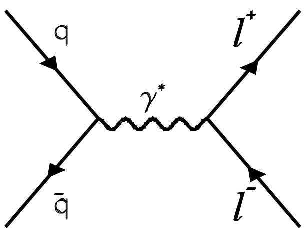
Difficulties:

- Absolute cross sections (K-factor is needed)
- Transverse momentum distributions (much larger $\langle p_T \rangle$ than expected)

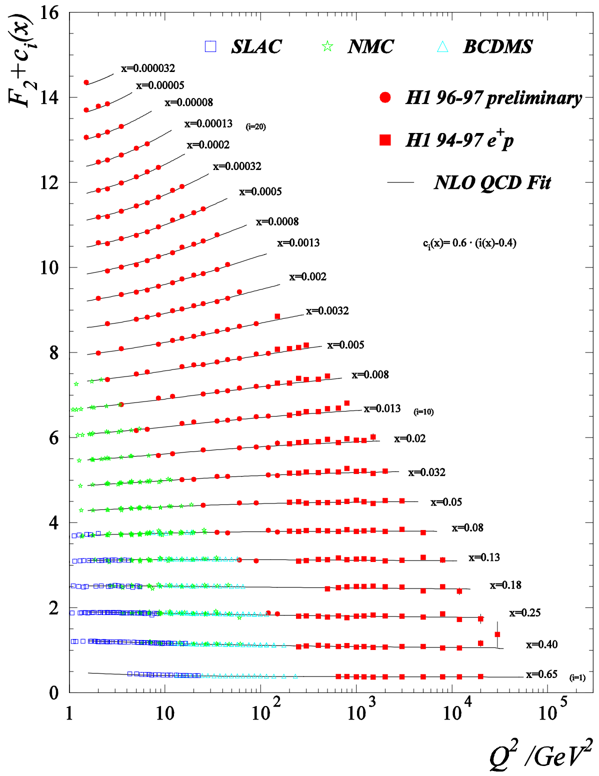
Complimentality between DIS and Drell-Yan

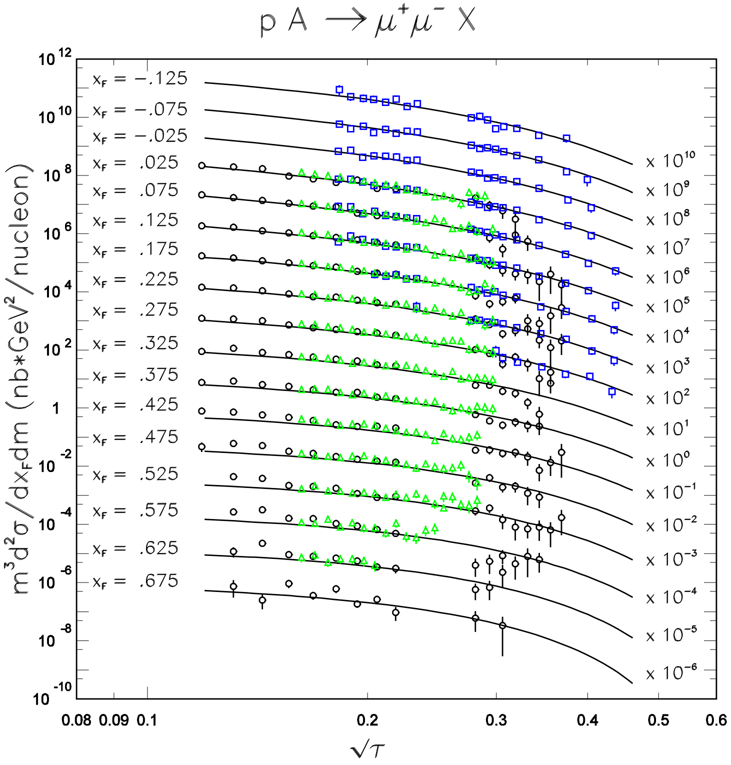
DIS





Drell-Yan





Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

Lepton-pair production provides unique information on parton distributions

$p+W \rightarrow \mu^{+}\mu^{-}X$

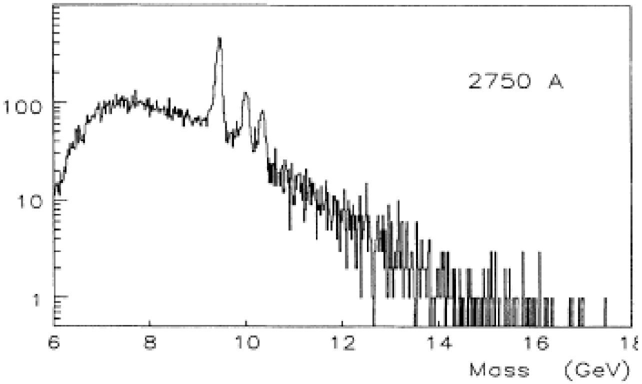
800 GeV/c

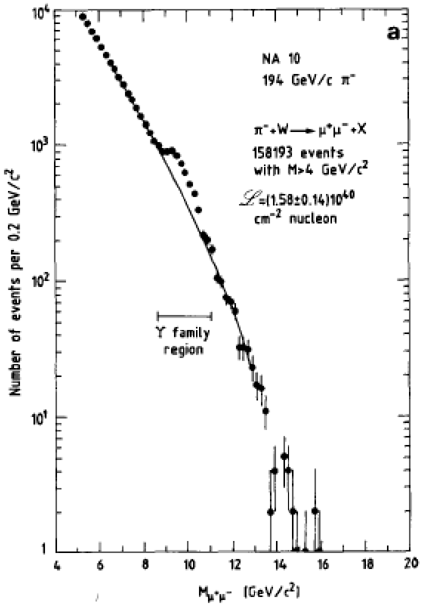
$\pi^{-}+W \rightarrow \mu^{+}\mu^{-}X$

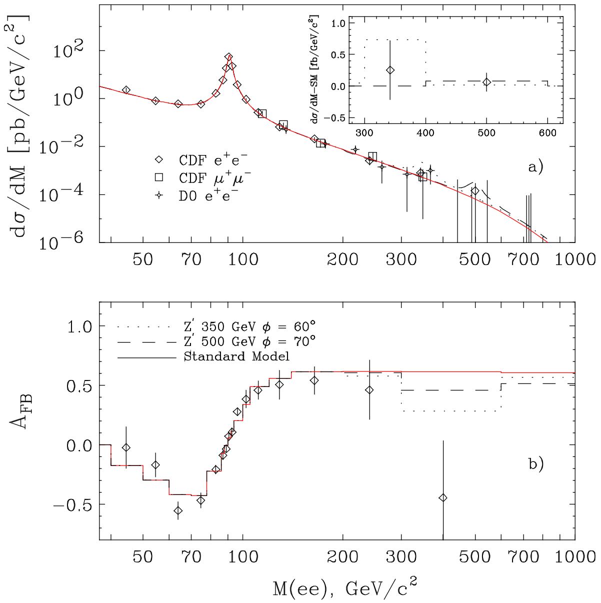
194 GeV/c

$\bar{p}+p \rightarrow l^{+}l^{-}X$

1.8 TeV







Probe antiquark distribution in nucleon

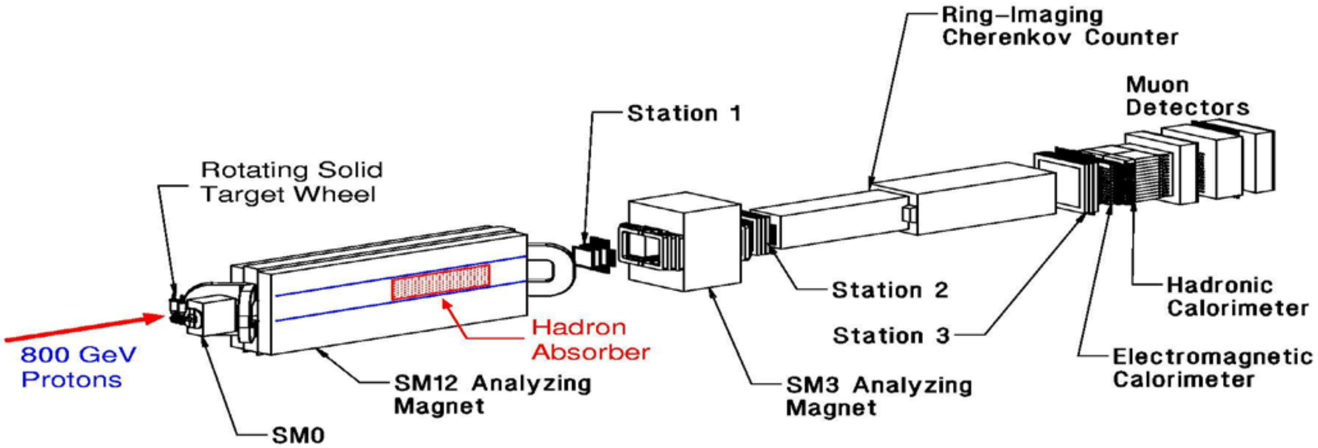
Probe antiquark distribution in pion

Probe antiquark distributions in antiproton

Unique features of D-Y: antiquarks, unstable hadrons…

Fermilab Dimuon Spectrometer

(E605 / 772 / 789 / 866 / 906)



1) Fermilab E772 (proposed in 1986 and completed in 1988)

   "Nuclear Dependence of Drell-Yan and Quarkonium Production"

2) Fermilab E789 (proposed in 1989 and completed in 1991)

   "Search for Two-Body Decays of Heavy Quark Mesons"

3) Fermilab E866 (proposed in 1993 and completed in 1996)

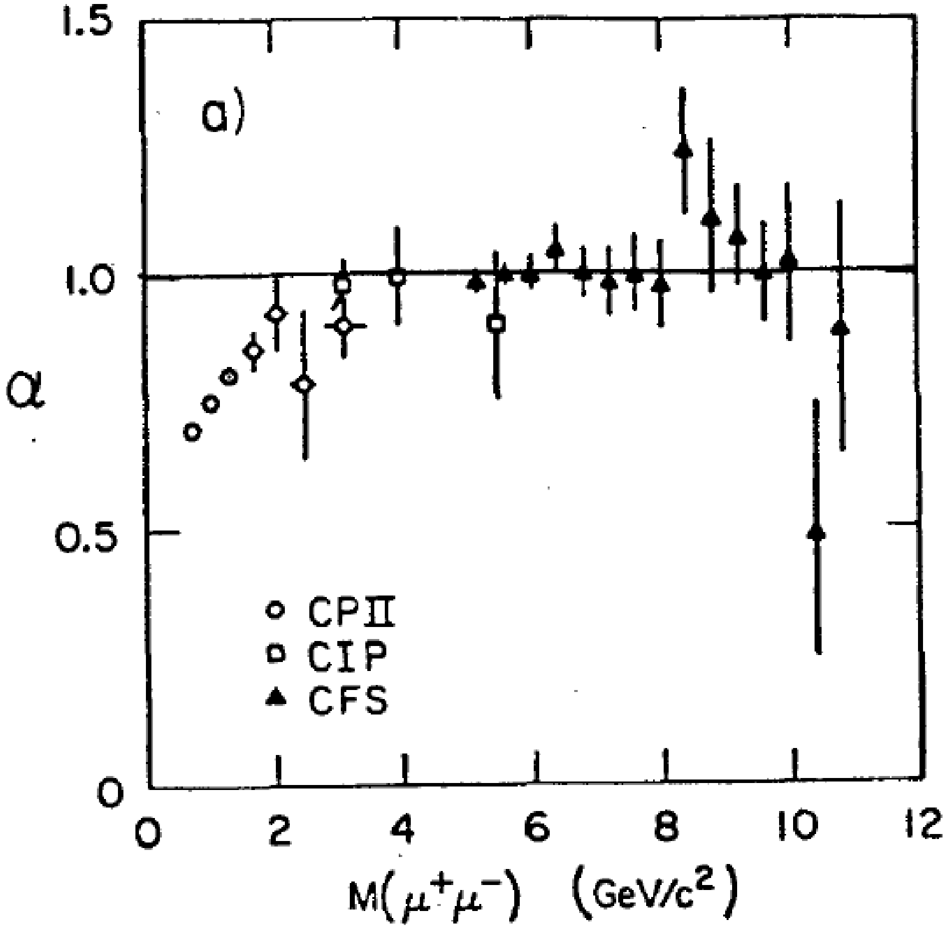
   "Determination of $\bar{d} / \bar{u}$ Ratio of the Proton via Drell-Yan"

4) Fermilab E906 (proposed in 1999, will run in 2011-2013)

   "Drell-Yan with the FNAL Main Injector"

Nuclear dependence of the Drell-Yan process

- As an electromagnetic process, the Drell-Yan cross section is expected to depend linearly on the nuclear mass number A



$$\sigma = \sigma_0 A^{\alpha}$$

σ_0: cross section

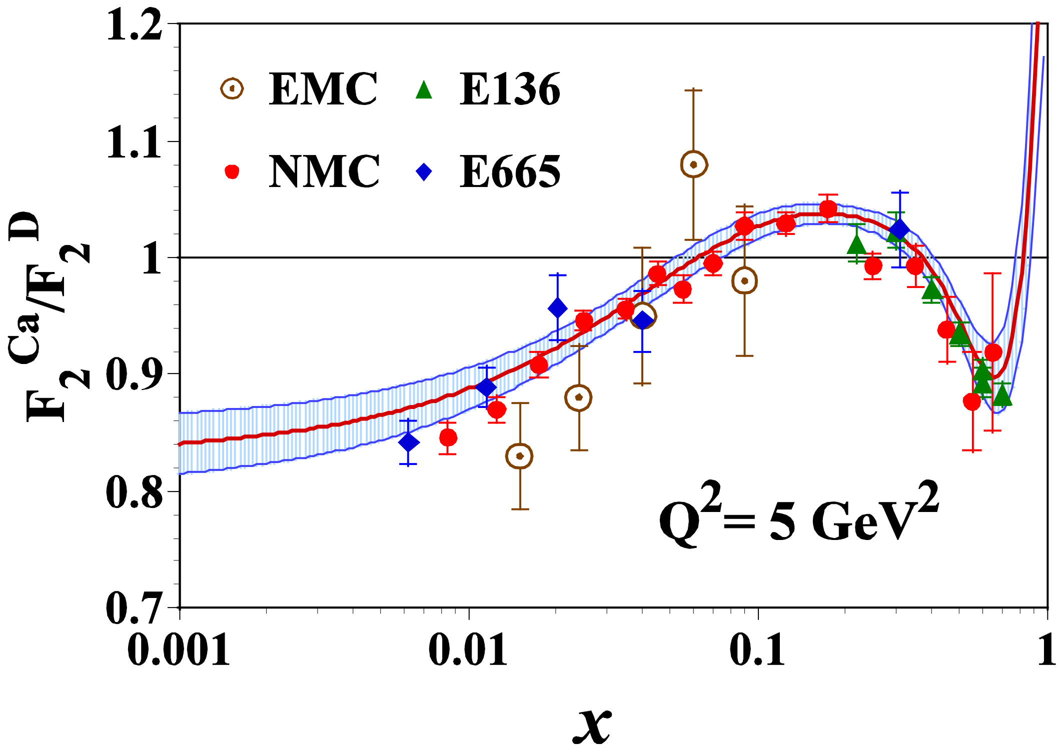
on a nucleon

(From review article of Kenyon in 1982)

α is consistent with 1

Modification of Parton Distributions in Nuclei

EMC effect observed in DIS



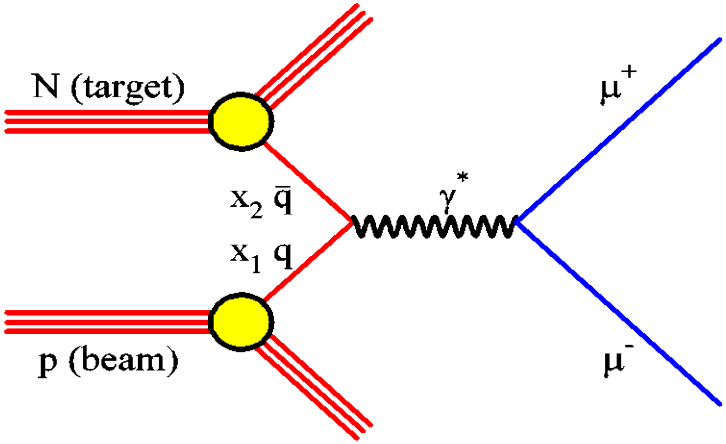
(Ann. Rev. Nucl. Part. Phys., Geesaman, Sato and Thomas)

F_2 contains contributions from quarks and antiquarks

How are the antiquark distributions modified in nuclei?

Drell-Yan on nuclear targets

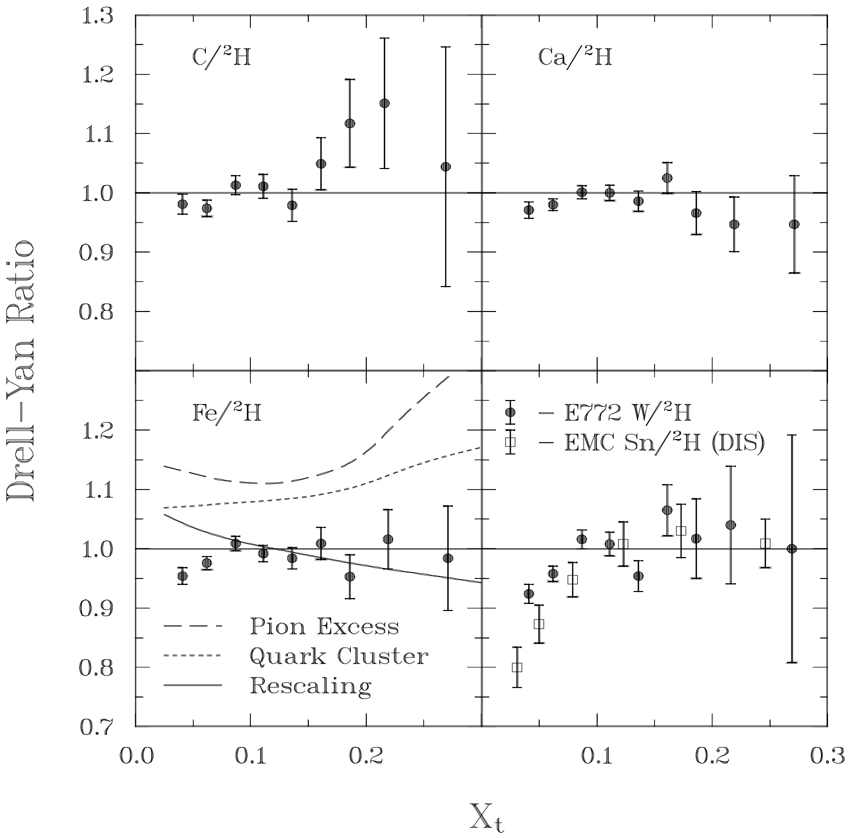
The Drell-Yan Process: $pN \to \mu^+\mu^- X$

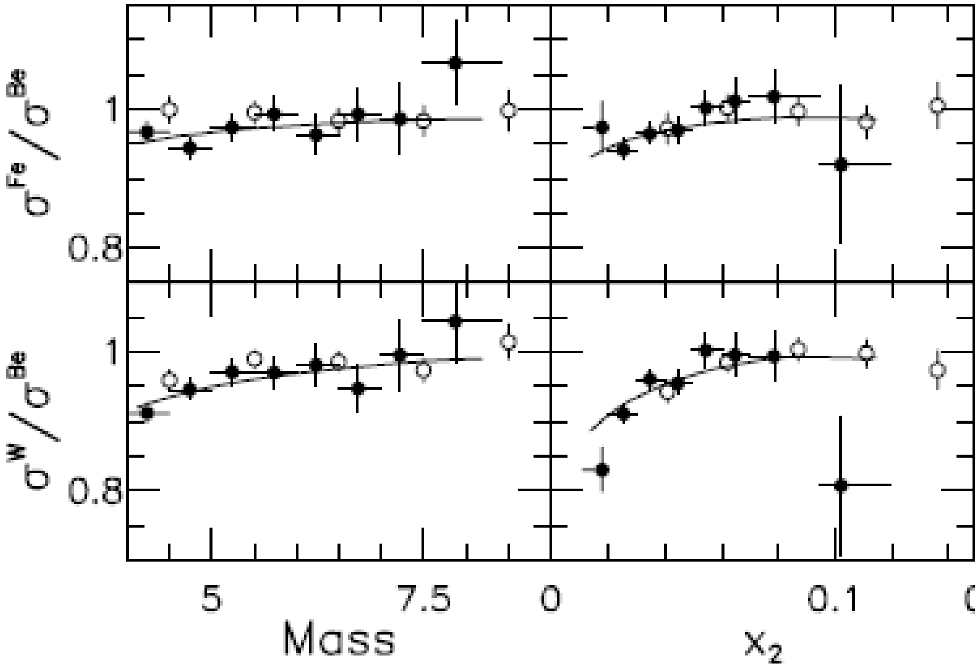


$$\frac{\sigma^{pA}}{\sigma^{pd}} \approx \frac{\bar{u}_A(x)}{\bar{u}_N(x)}$$

The x-dependence of $\bar{u}_A(x)/\bar{u}_N(x)$ can be directly measured

Drell-Yan on nuclear targets





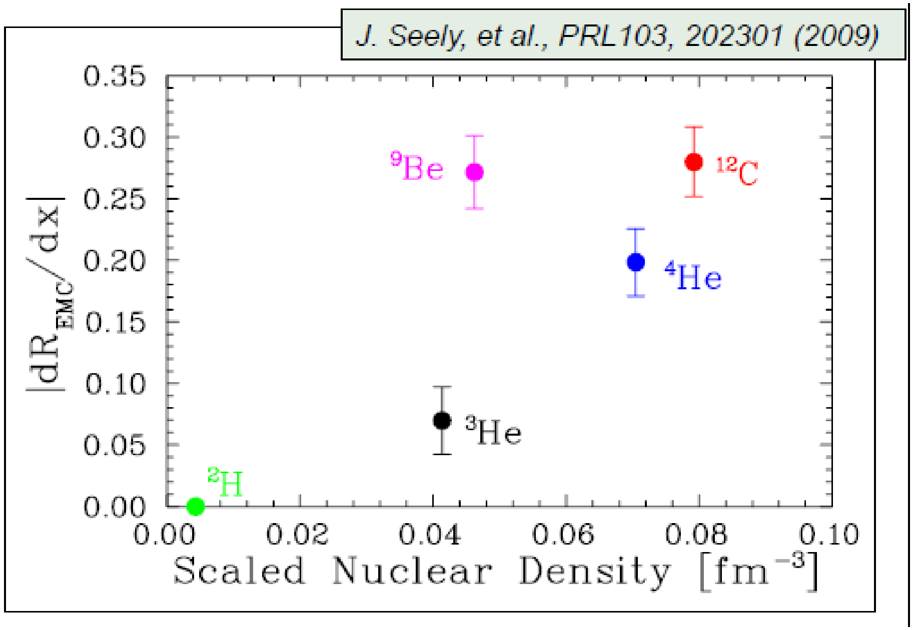
PRL 64 (1990) 2479

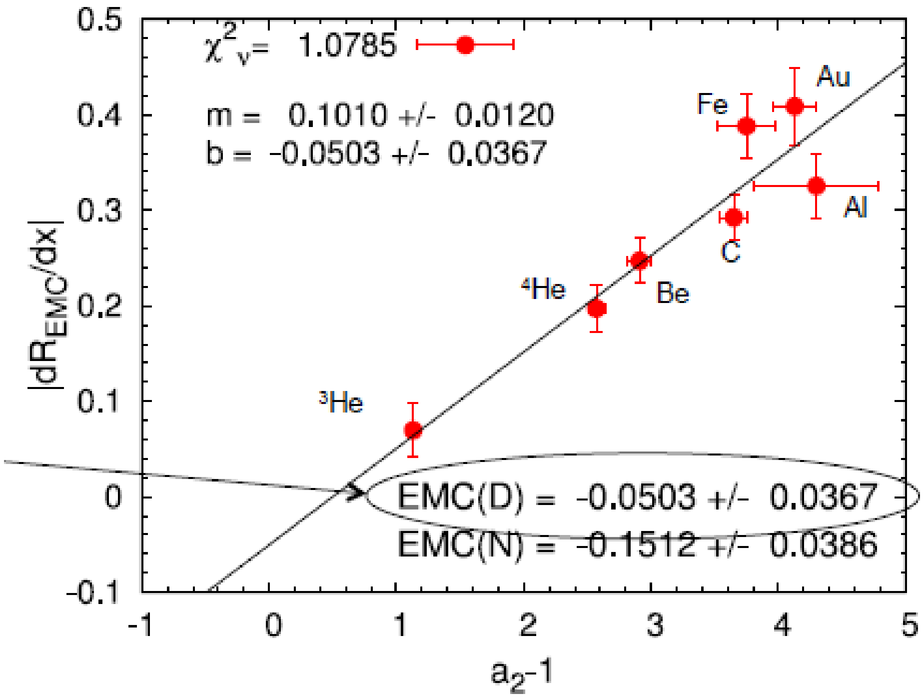
PRL 83 (1999) 2304

No evidence for enhancement of antiquark in niclei !?

E906 will extend the measurement to larger *x*

EMC-SRC Correlation


J. Seely, et al., PRL103, 202301 (2009)

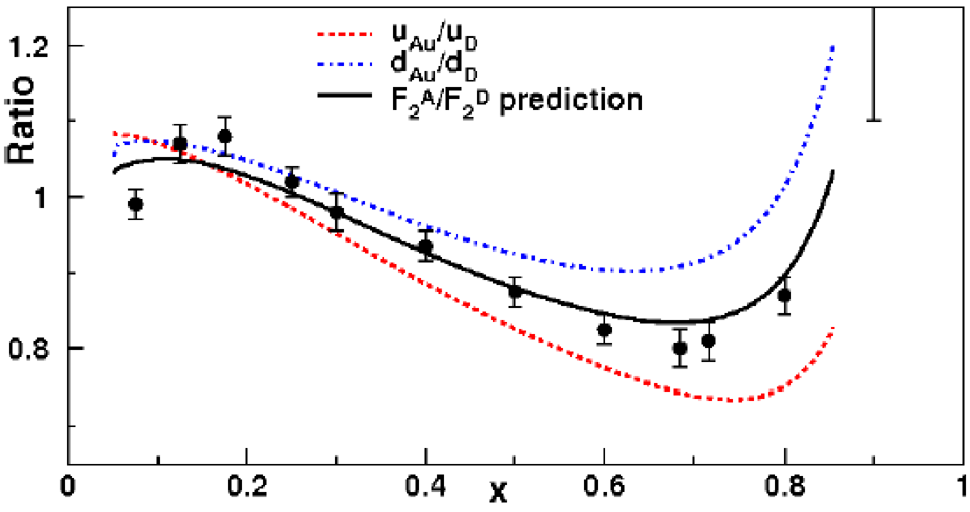


From D. Gaskell's talk

Possible tests for EMC-SRC correlation with Drell-Yan

- Expect to see the same EMC-SRC correlation for Drell-Yan nuclear dependence (effect should be identical for valence and sea quarks)
  - Can be tested at Fermilab E906
  - ^{9}Be target should be measured
- Expect no up-down quark flavor dependence for SRC (since SRC is dominated by isoscalar p-n correlation)
  - Can be tested by pion or antiproton induced Drell-Yan

Flavor dependence of the EMC effects ?



Isovector mean-field generated in Z≠N nuclei can modify nucleon’s *u* and *d* PDFs in nuclei

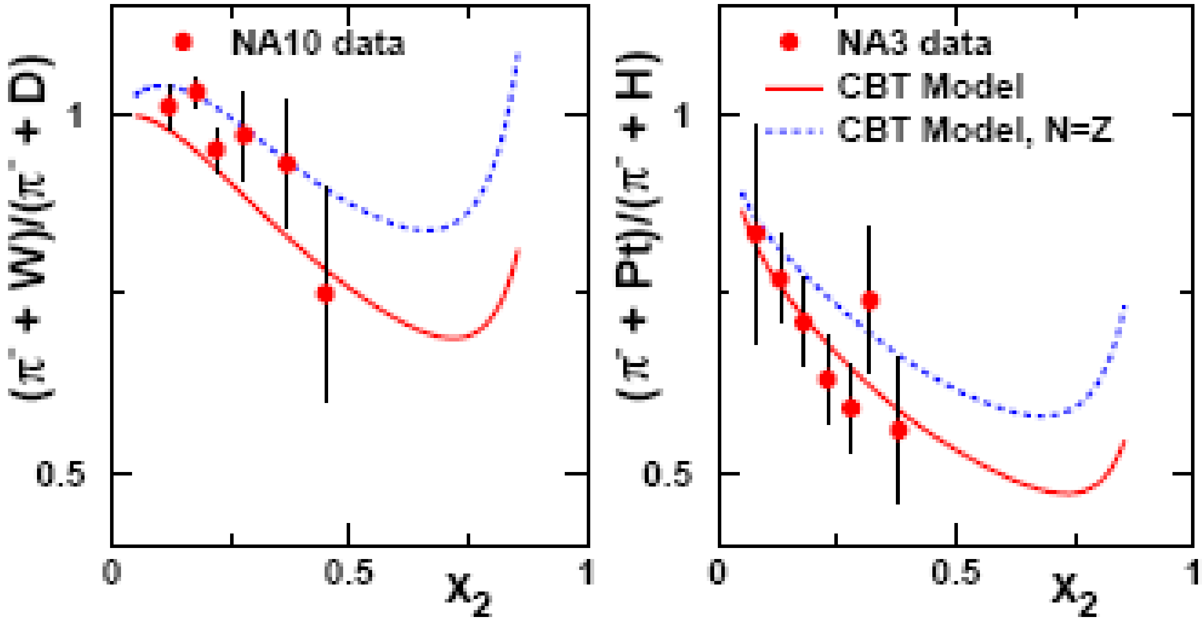
Cloet, Bentz, and Thomas, arXiv:0901.3559

How can one check this prediction?

- SIDIS (JLab proposal) and PVDIS (P.Souder)
- Pion-induced Drell-Yan

Pion-induced Drell-Yan and the flavor-dependent EMC effect

$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

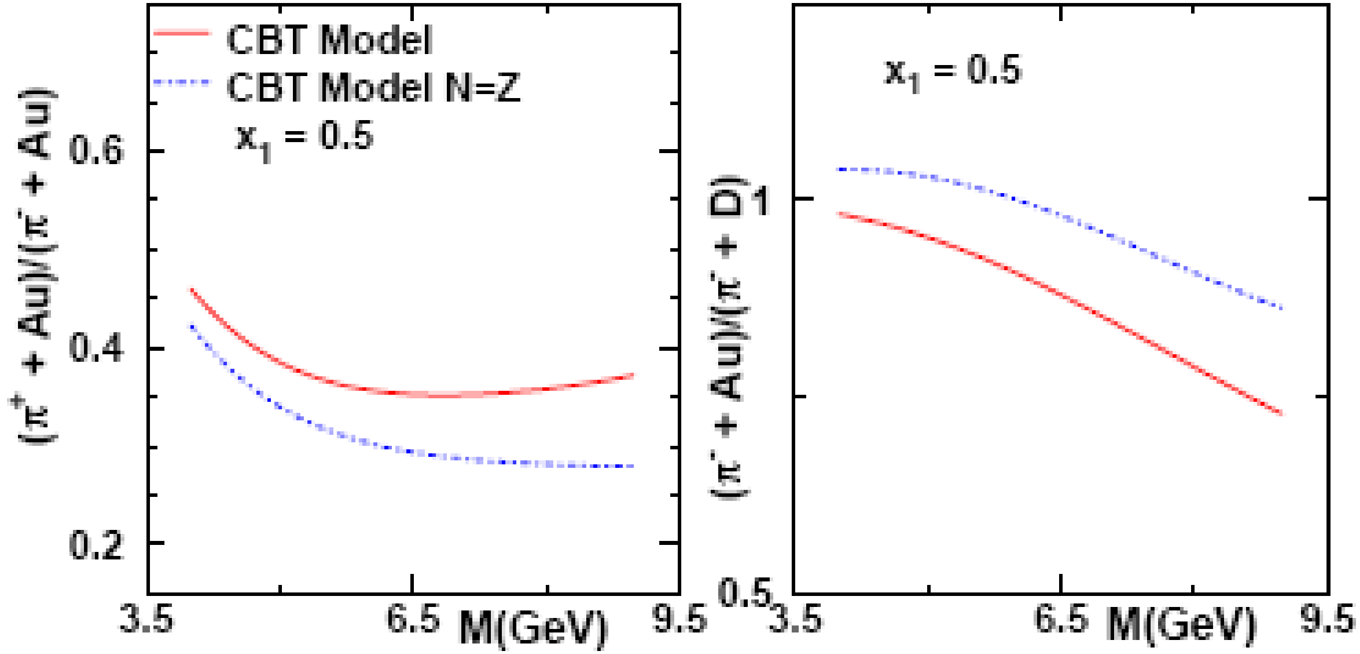


Red (blue) curves correspond to flavor-dependent (independent) EMC

(D. Dutta, JCP, Cloet, Gaskell, arXiv: 1007.3916)

Pion-induced Drell-Yan and the flavor-dependent EMC effect

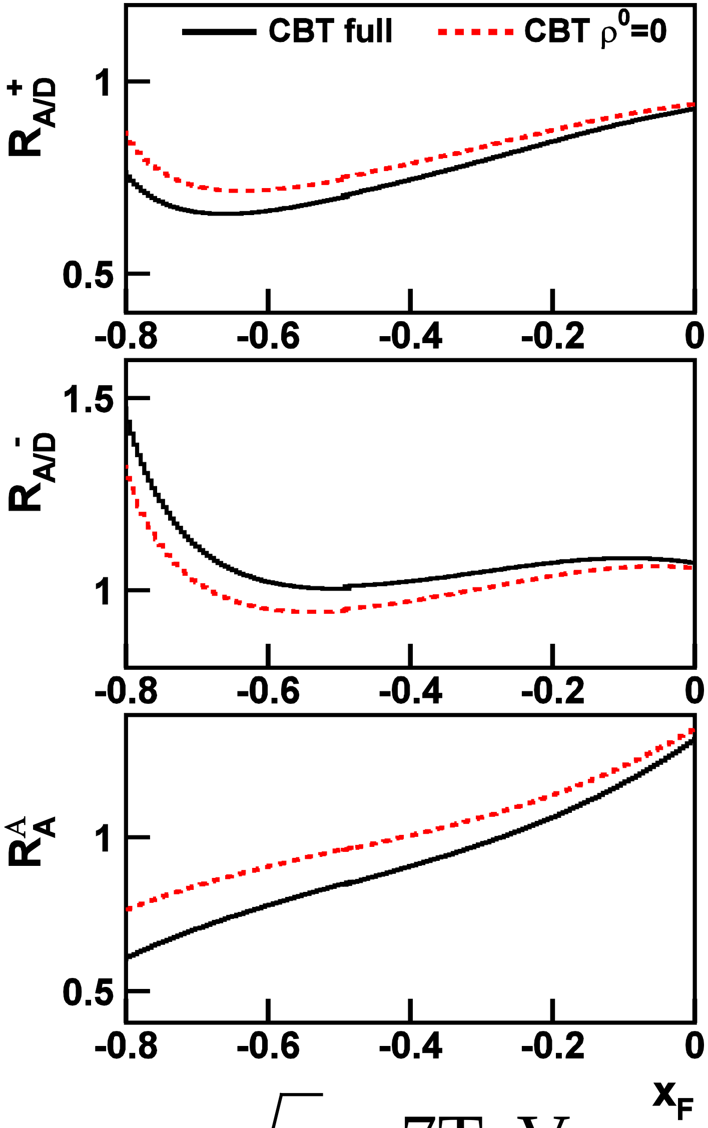
$$\frac{\sigma^{DY}(\pi^{+}+A)}{\sigma^{DY}(\pi^{-}+A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^{-}+A)}{\sigma^{DY}(\pi^{-}+D)} \approx \frac{u_A(x)}{u_D(x)}$$



160 GeV pion beam

Drell-Yan data from COMPASS with pion beams could provide important new information

W-production at LHC and the flavor-dependent EMC effect



$$\sqrt{s} = 7\mathrm{TeV}$$

$$R^{+}_{A/D} \equiv \frac{d\sigma(p+A \to W^{+}+x)}{d\sigma(p+D \to W^{+}+x)} \approx \frac{u_A(x_2)}{u_D(x_2)}$$

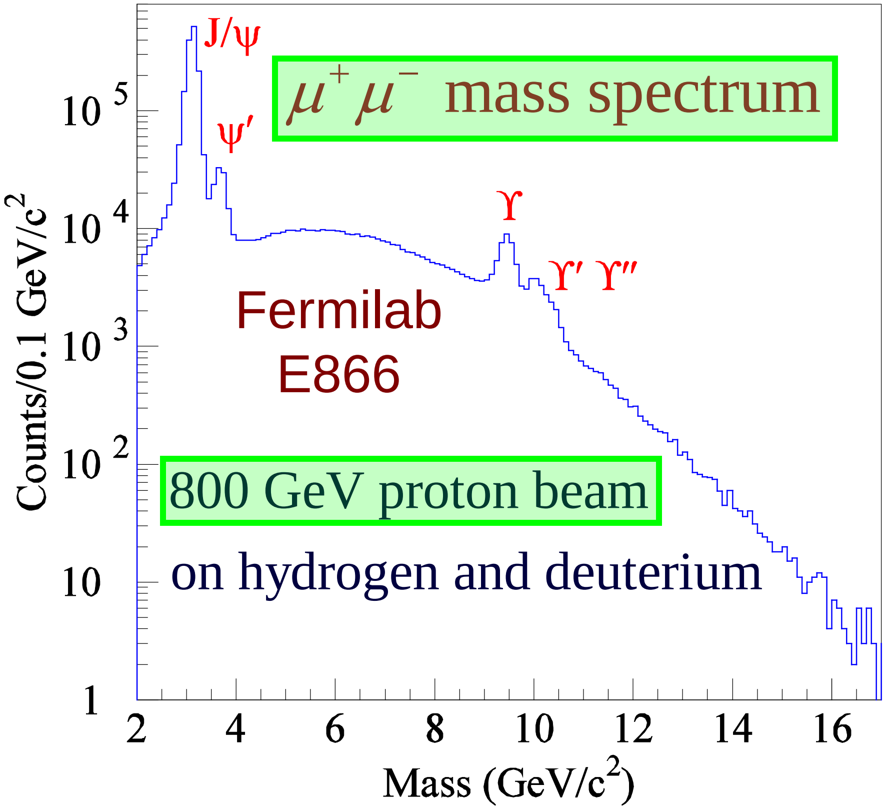
$$R^{-}_{A/D} \equiv \frac{d\sigma(p+A \to W^{-}+x)}{d\sigma(p+D \to W^{-}+x)} \approx \frac{d_A(x_2)}{d_D(x_2)}$$

$$R^{\pm}_{A} \equiv \frac{d\sigma(p+A \to W^{+}+x)}{d\sigma(p+A \to W^{-}+x)} \approx \frac{\bar{d}_p(x_1)}{\bar{u}_p(x_1)} \frac{u_A(x_2)}{d_A(x_2)}$$

(Chang, Cloet, Dutta, JCP, 1109.3108)

$\bar{d}/\bar{u}$ flavor asymmetry from Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

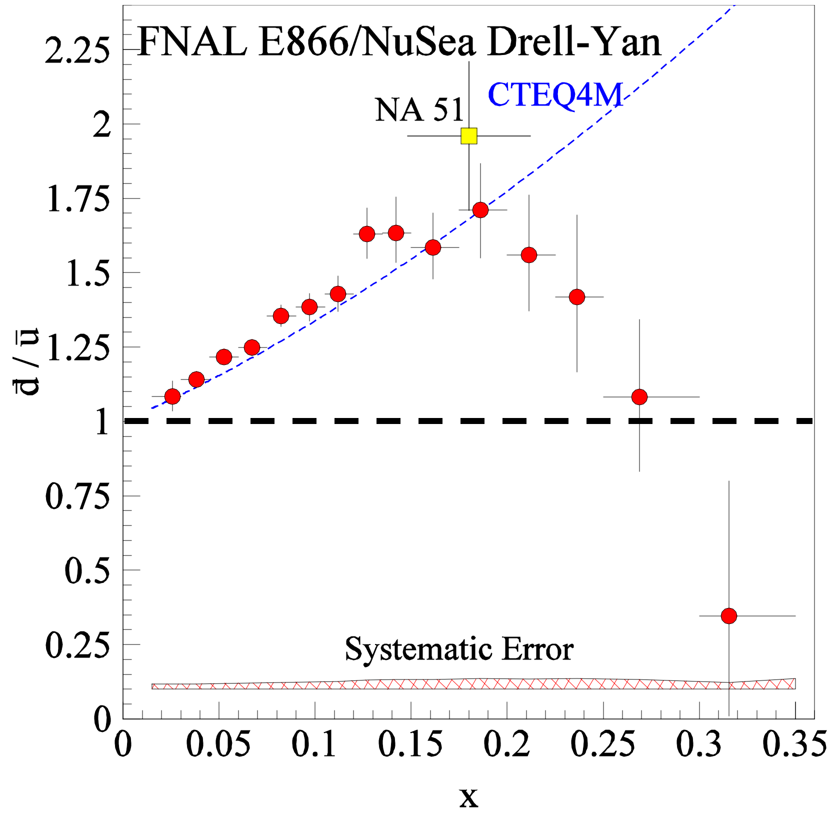


$\mu^+\mu^-$ mass spectrum

Fermilab
E866

800 GeV proton beam

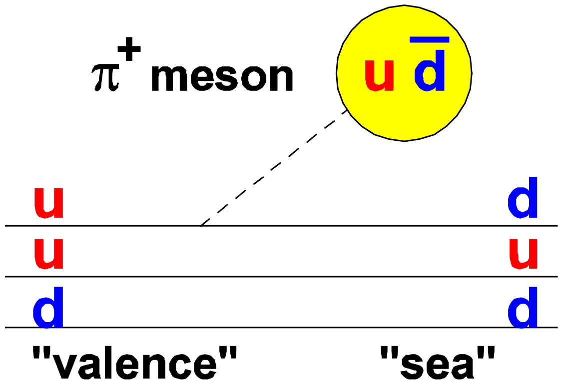
on hydrogen and deuterium



at $x_1 > x_2$: Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \sim \frac{1}{2}(1+\bar{d}(x_2)/\bar{u}(x_2))$

Origins of $\bar{u}(x) \neq \bar{d}(x)$?

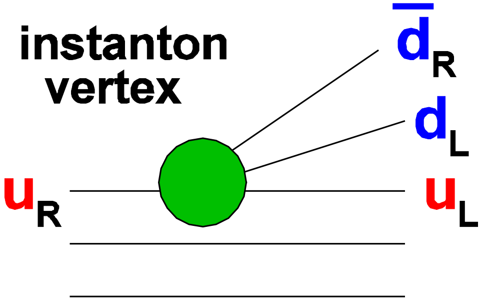
Meson Cloud Models



Chiral-Quark Soliton Model

- nucleon = chiral soliton
- expand in 1/*Nc*
- Quark degrees of freedom in a pion mean-field

Instantons



Theory: Thomas, Miller, Kumano, Ma, Londergan, Henley, Speth, Hwang, Melnitchouk, Liu, Cheng/Li, etc.

(For reviews, see Speth and Thomas (1997), Kumano (hep-ph/9702367), Garvey and Peng (nucl-ex/0109010))

Theses models also have implications on

- asymmetry between $s(x)$ and $\bar{s}(x)$
- flavor structure of the polarized sea

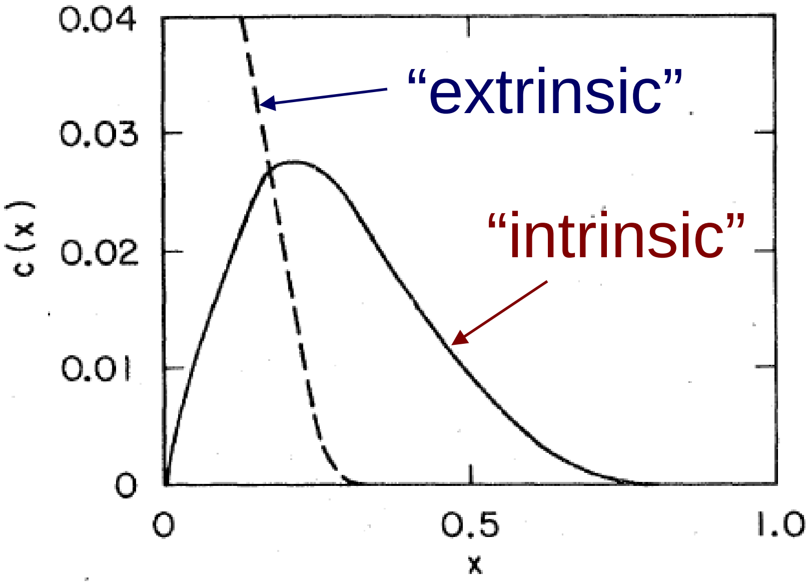
Meson cloud has significant contributions to sea-quark distributions

Search for the “intrinsic” quark sea

In 1980, Brodsky, Hoyer, Peterson, Sakai (BHPS)
suggested the existence of “intrinsic” charm

$$| p\rangle = P_{3q} \, | uud\rangle + P_{5q} \, | uudQ\overline{Q}\rangle + \cdots\cdots$$

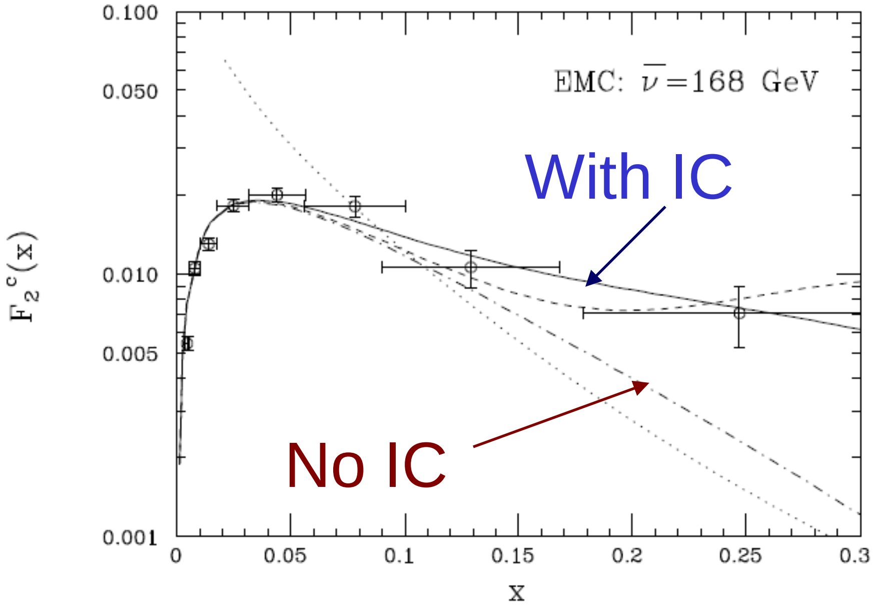
The "intrinsic"-charm from $| uudc\overline{c}\rangle$ is "valence"-like and peak at large x unlike the "extrinsic" sea ($g \to c\overline{c}$)



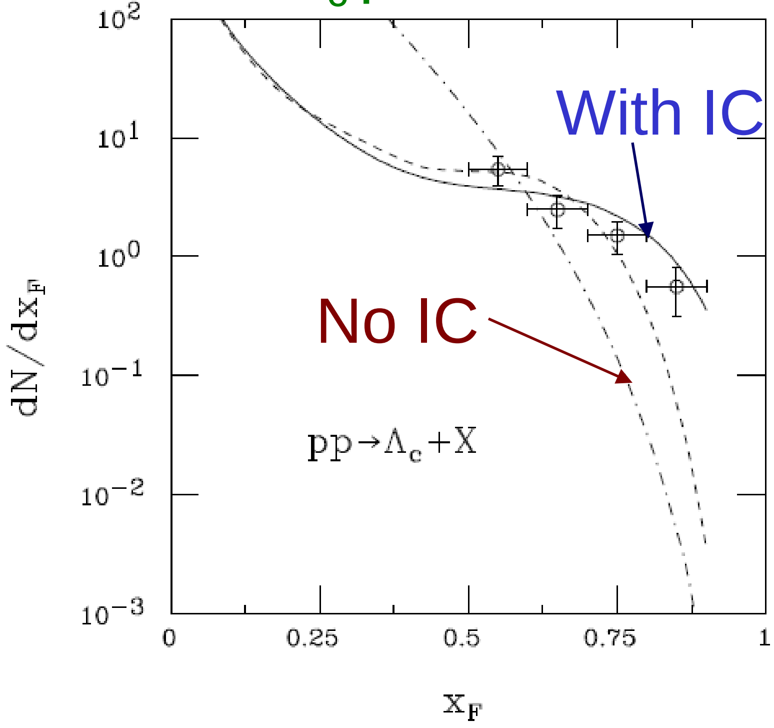
The $| uudc\overline{c}\rangle$ intrinsic-charm can lead to large contribution to charm production at large x

“Evidence” for the “intrinsic” charm (IC)

DIS data



Λ_c production

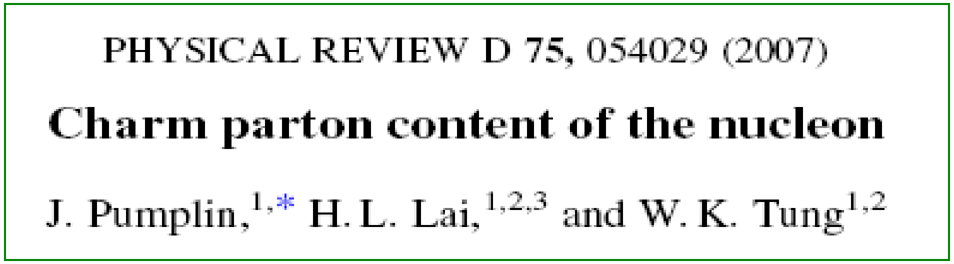


Gunion and Vogt (hep-ph/9706252)

“Evidence” appears to be rather weak

(subject to the uncertainties of charmed-quark parametrization in the PDF)

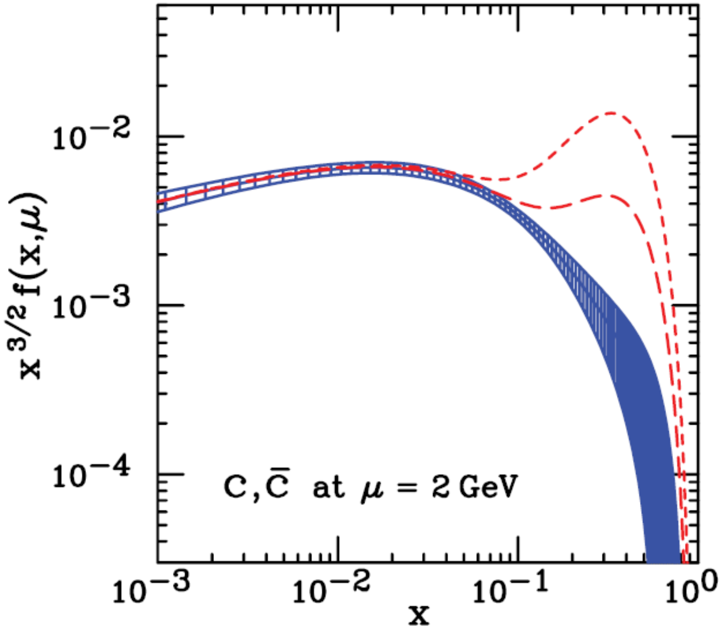
A global fit by CTEQ to extract intrinsic-charm



PHYSICAL REVIEW D 75, 054029 (2007)

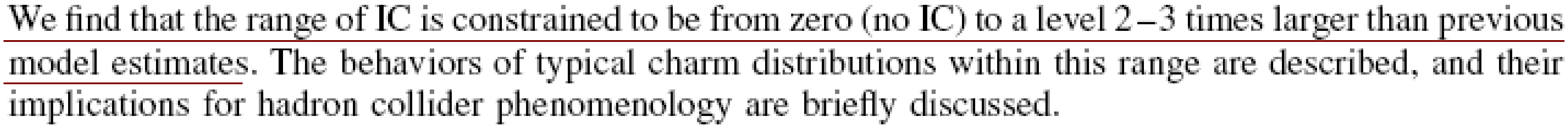
Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)



We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

Search for the lighter “intrinsic” quark sea

$$| p\rangle = P_{3q} \, | uud\rangle + P_{5q} \, | uudQ\bar{Q}\rangle + \cdots\cdots$$

No conclusive experimental evidence
for intrinsic-charm so far

Are there experimental evidences for the intrinsic
$|uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle$ 5-quark states ?

$$\boxed{P_{5q} \sim 1/m_Q^2}$$

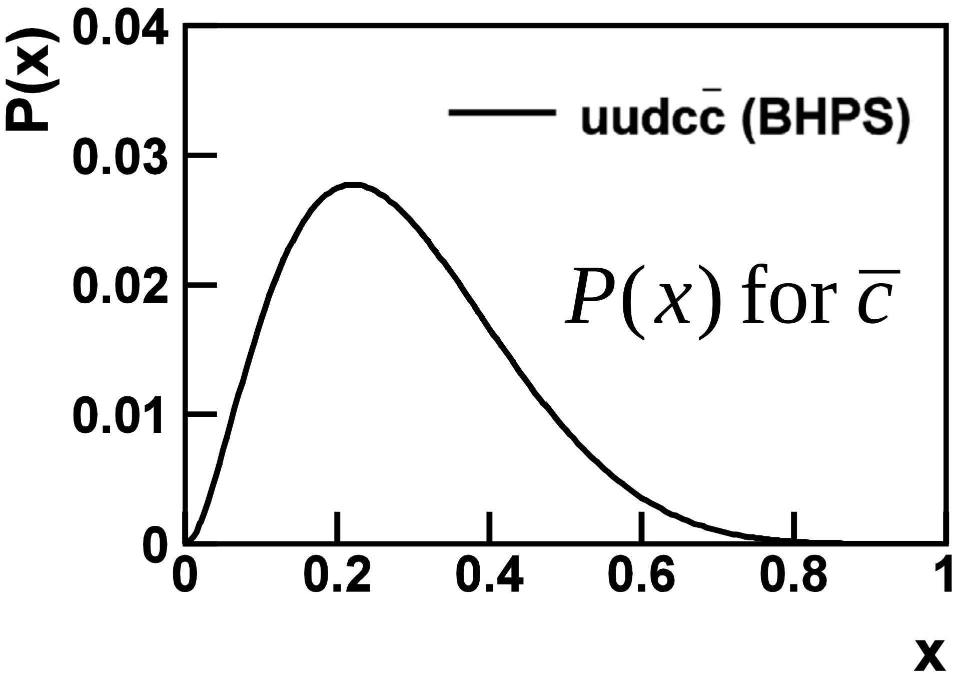
The 5-quark states for lighter
quarks have larger probabilities!

x-distribution for "intrinsic" charm

$$|\,p\rangle = P_{3q}\,|\,uud\rangle + P_{5q}\,|\,uudQ\overline{Q}\rangle + \cdots\cdots$$

Brodsky et al. (BHPS) give the following probability for quark *i* (mass *m*$_i$) to carry momentum *x*$_i$

$$P(x_1,\cdots,x_5) = N_5\delta(1-\sum_{i=1}^{5} x_i)[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}$$



In the limit of large mass for quark Q (charm):

$$P(x_5) = \frac{1}{2}\tilde{N}_5 x_5^2[(1-x_5)(1+10x_5+x_5^2) \\ -2x_5(1+x_5)ln(1/x_5)$$

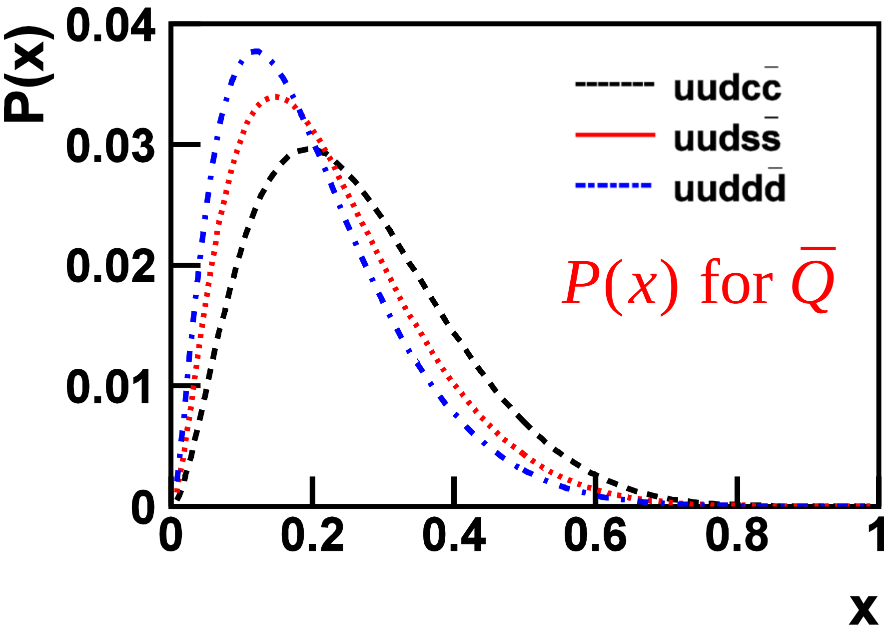
An analytical expression for *P(x)* is obtained

x-distribution for “intrinsic” light-quark sea

$$| p\rangle = P_{3q}\,| uud\rangle + P_{5q}\,| uudQ\bar{Q}\rangle + \cdots\cdots$$

Brodsky et al. (BHPS) give the following probability for quark *i* (mass m_i) to carry momentum x_i

$$P(x_1,\cdots,x_5) = N_5\delta(1-\sum_{i=1}^{5} x_i)[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}$$



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One can calculate $P(x)$ for antiquark $\bar{Q}$ $(\bar{c}, \bar{s}, \bar{d})$ numerically

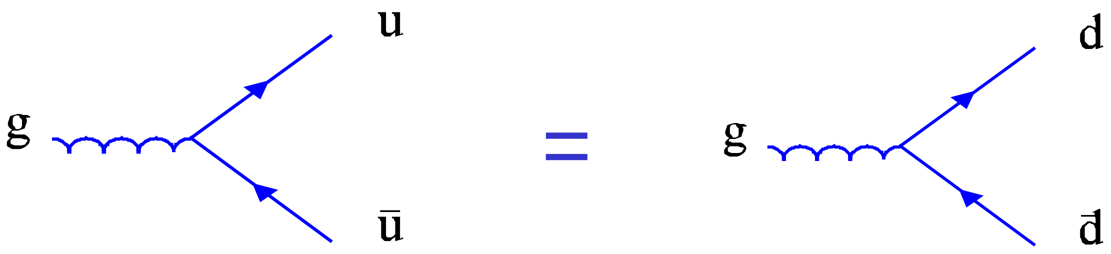
How to separate the “intrinsic sea” from the “extrinsic sea”?

- Select experimental observables which have no contributions from the “extrinsic sea”
- “Intrinsic sea” and “extrinsic sea” are expected to have different *x*-distributions
  - Intrinsic sea is “valence-like” and is more abundant at larger *x*
  - Extrinsic sea is more abundant at smaller *x*

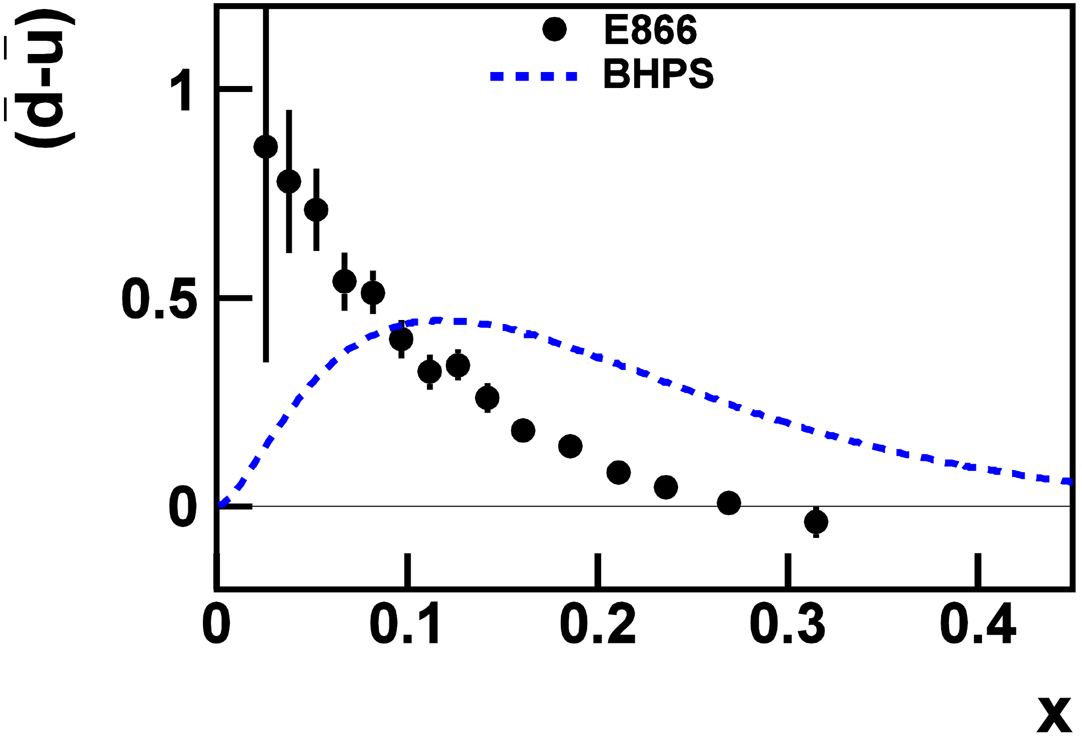
How to separate the “intrinsic sea” from the “extrinsic sea”?

- Select experimental observables which have no contributions from the “extrinsic sea”

$$\bar{d} - \bar{u} \text{ has no contribution from extrinsic sea } (g \rightarrow \bar{q}q)$$
$$\text{and is sensitive to "intrinsic sea" only}$$



Comparison between the $\bar{d}(x)-\bar{u}(x)$ data with the intrinsic 5-*q* model

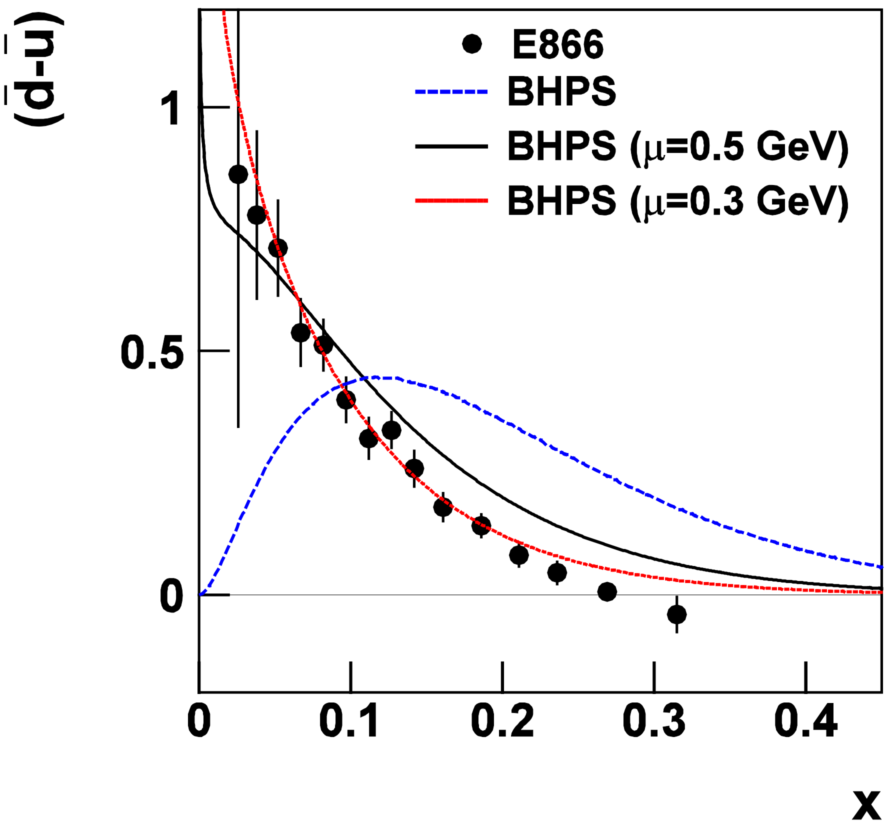


The data have very different shape compared to the BHPS 5-q model

E866 data measured at $\langle Q^2\rangle = 54$ GeV^2

Need to evolve the 5-q model prediction from the initial scale μ to Q^2=54 GeV^2

Comparison between the $\bar{d}(x) - \bar{u}(x)$ data with the intrinsic 5-*q* model



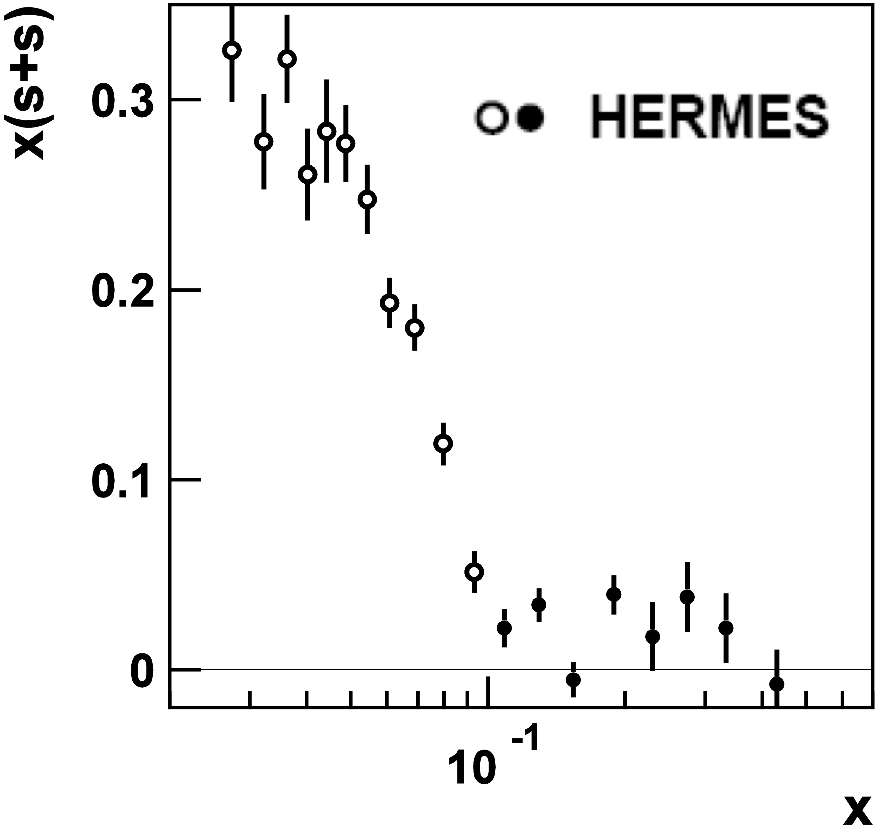
The data are in good agreement with the 5-q model after evolution from the initial scale μ to Q^2=54 GeV^2

The difference in the two 5-quark components can also be determined

(W. Chang and JCP , PRL 106, 252002 (2011))

$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$

Comparison between the $s(x)+\overline{s}(x)$ data with the intrinsic 5-*q* model

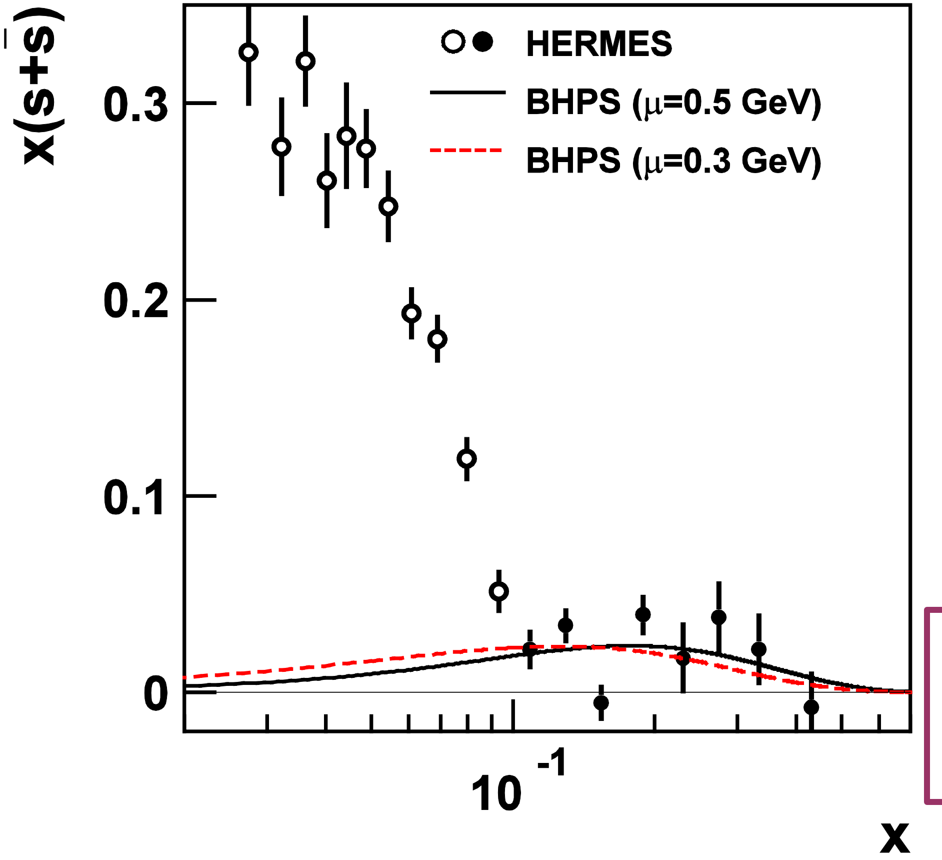


$s(x)+\overline{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$

The data appear to consist of two different components (intrinsic and extrinsic?)

HERMES collaboration, Phys. Lett. B666, 446 (2008)

Comparison between the $s(x) + \bar{s}(x)$ data with the intrinsic 5-q model



(W. Chang and JCP, PL B704, 197(2011))

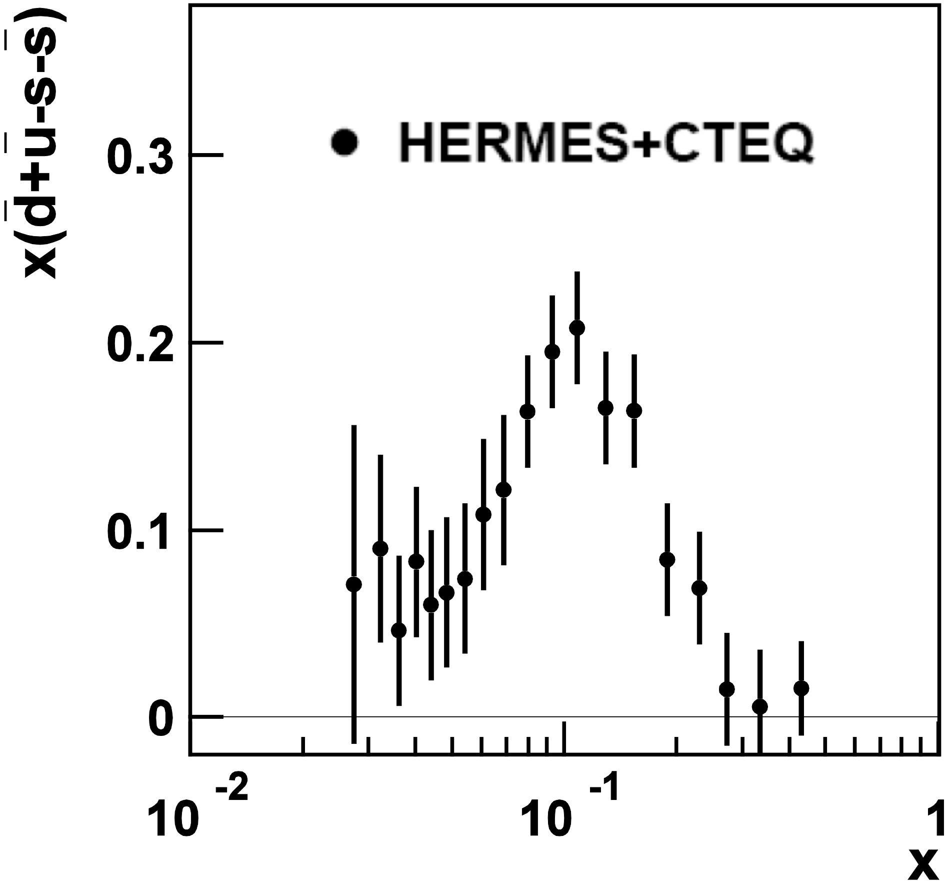
$s(x) + \bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$

Assume $x > 0.1$ data are dominate by intrinsic sea (and $x < 0.1$ are from QCD sea)

This allows the extraction of the intrinsic sea for strange quarks

$$\boxed{P_5^{uuds\bar{s}} = 0.024}$$

Comparison between the $\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)$ data with the intrinsic 5-*q* model



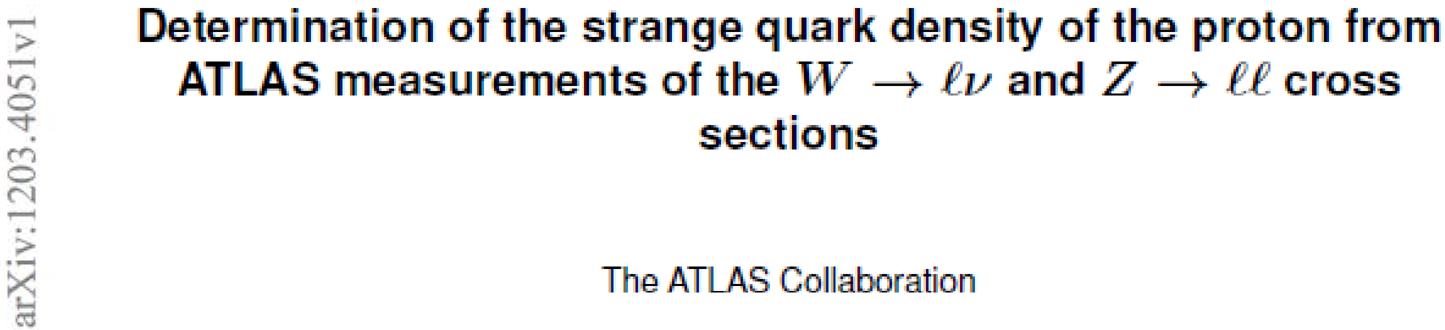
$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$\bar{u}+\bar{d}-s-\bar{s}$ has no contribution from extrinsic sea

A valence-like *x*-distribution is observed

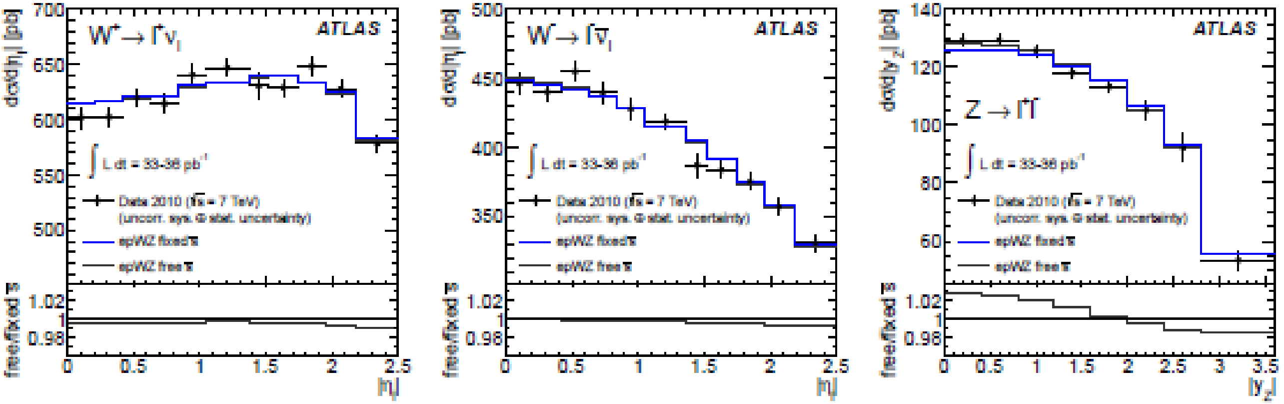
Is the “extrinsic” sea flavor-symmetric for *u*, *d*, and *s*?



arXiv:1203.4051v1

Determination of the strange quark density of the proton from ATLAS measurements of the $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ cross sections

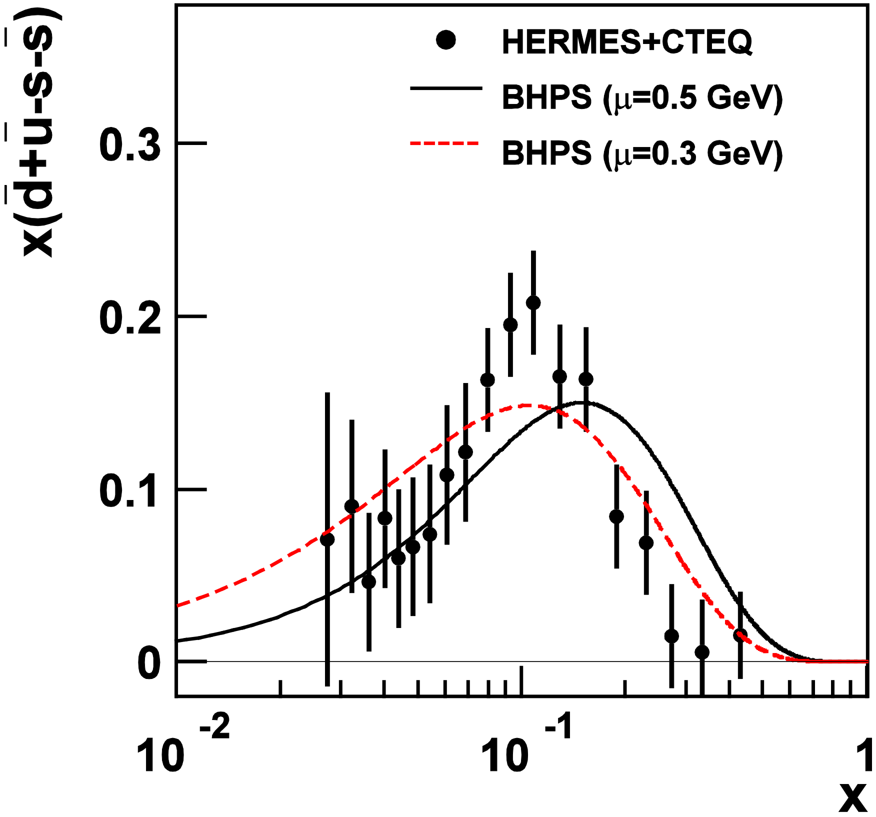
The ATLAS Collaboration



$$\boxed{r_s = 0.5(s+\bar{s})/\bar{d}}$$

$$\boxed{r_s = 1.00^{+0.25}_{-0.28}, \text{ at Bjorken } x = 0.023}$$

Comparison between the $\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)$ data with the intrinsic 5-*q* model



$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$$\bar{u}+\bar{d}-s-\bar{s}$$

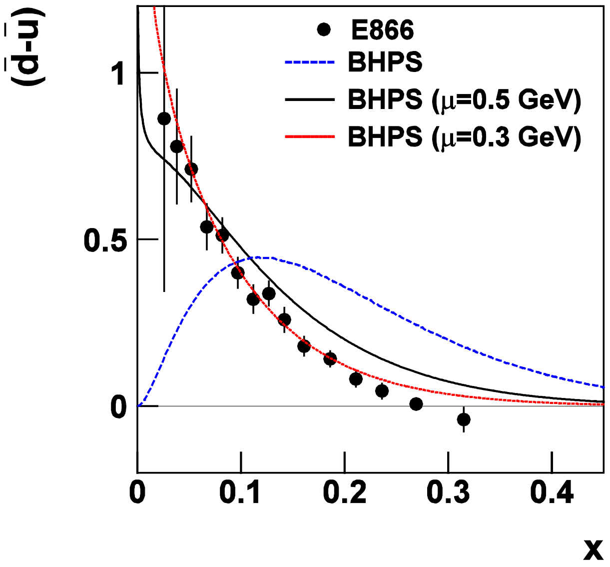
$$\sim P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}$$

(not sensitive to extrinsic sea)

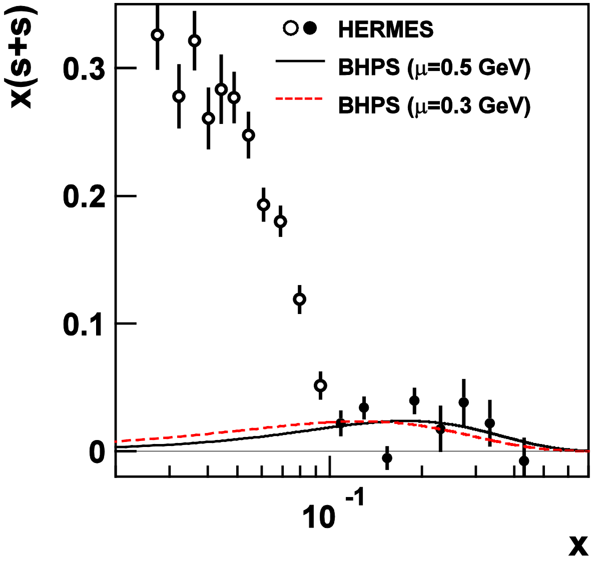
(W. Chang and JCP, PL B704, 197(2011))

$$\boxed{P_5^{uudu\bar{u}}+P_5^{uudd\bar{d}}-2P_5^{uuds\bar{s}}=0.314}$$

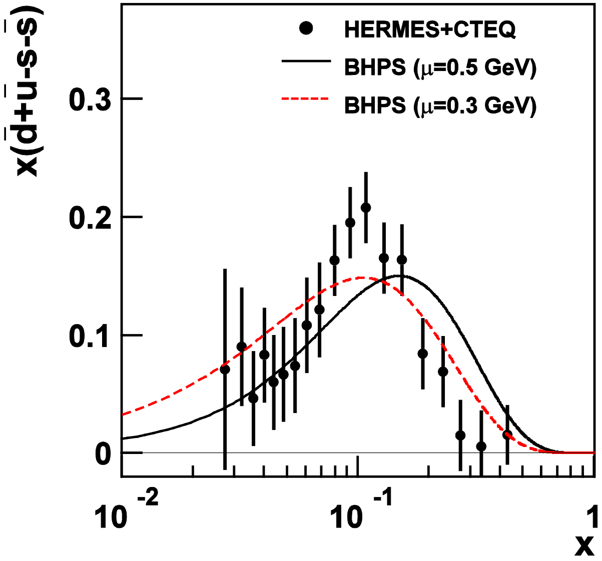
Extraction of the various five-quark components for light quarks



$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = 0.118$$



$$P_5^{uuds\bar{s}} = 0.024$$



$$P_5^{uudu\bar{u}} + P_5^{uudd\bar{d}} - 2P_5^{uuds\bar{s}} = 0.314$$

$$\boxed{P_5^{uudd\bar{d}} = 0.240; \;\; P_5^{uudu\bar{u}} = 0.122; \;\; P_5^{uuds\bar{s}} = 0.024}$$

Possible implications on the intrinsic charm

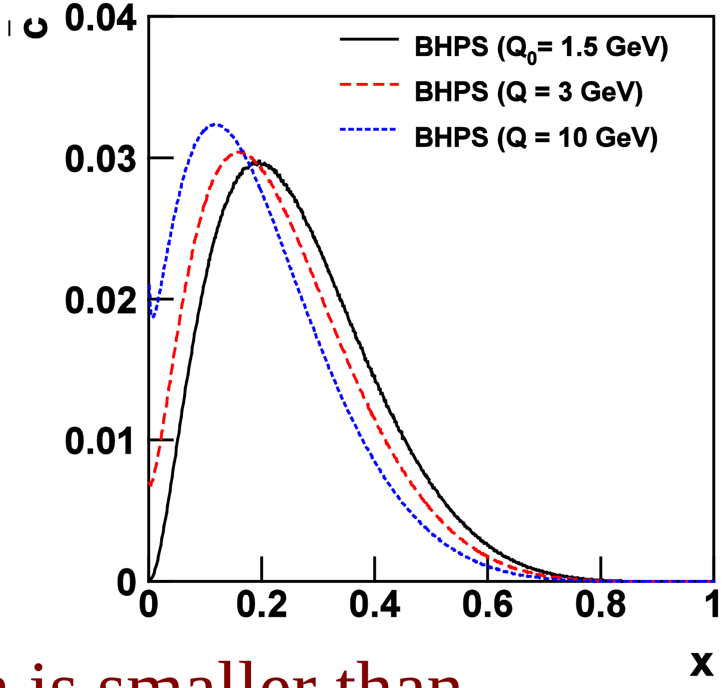
$$\boxed{P_5^{uudd\bar{d}} = 0.240;\ \ P_5^{uudu\bar{u}} = 0.122;\ \ P_5^{uuds\bar{s}} = 0.024}$$

Assuming

$$P_5^{uudQ\bar{Q}} \sim 1/m_Q^2$$

then

$$P_5^{uudc\bar{c}} \sim 0.1 P_5^{uuds\bar{s}} \sim 0.003$$



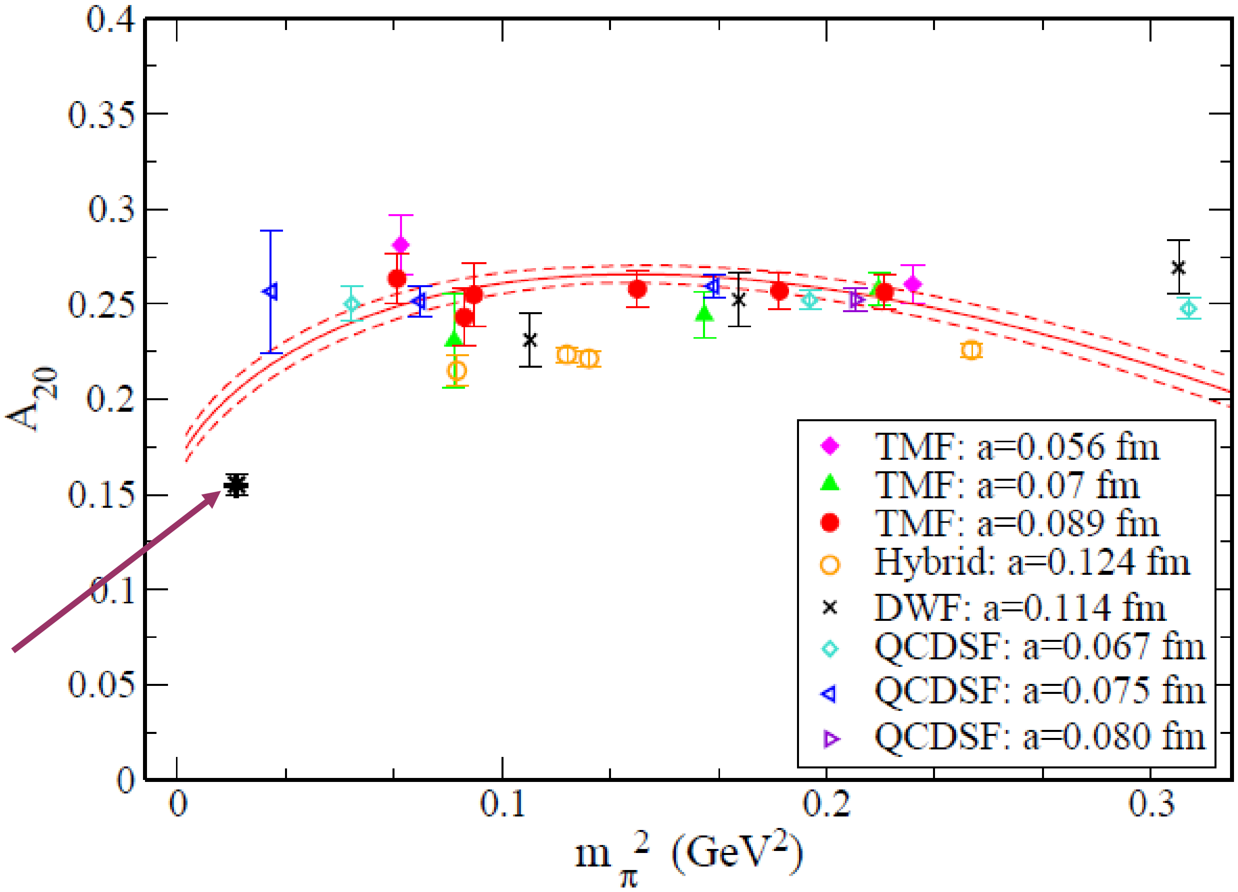
- Probability of intrinsic-charm is smaller than expected
- Evolution would shift the intrinsic-charm distribution to smaller-*x*

Future prospect on intrinsic sea

- Kaon production in SIDIS at COMPASS and 12 GeV JLab for additional information on s and s-bar?
- Kaon-induced Drell-Yan at COMPASS for probing s and s-bar?
- Open-charm production at forward rapidity at RHIC and LHC.
- Intrinsic sea for hyperons and mesons?
- Connection between intrinsic sea and meson-cloud?
- Spin dependence of intrinsic sea?

Lattice QCD on A_{20} and flavor asymmetry

$$A_{20}=\int_0^1 x[u(x)-d(x)+\bar{u}(x)-\bar{d}(x)]dx$$



data

Alexandrou
et al.,
1011.3660

$A_{20}\sim 0.20$ from lattice QCD; $A_{20}\sim 0.15$ from data

Lattice QCD on A_{20} and flavor asymmetry

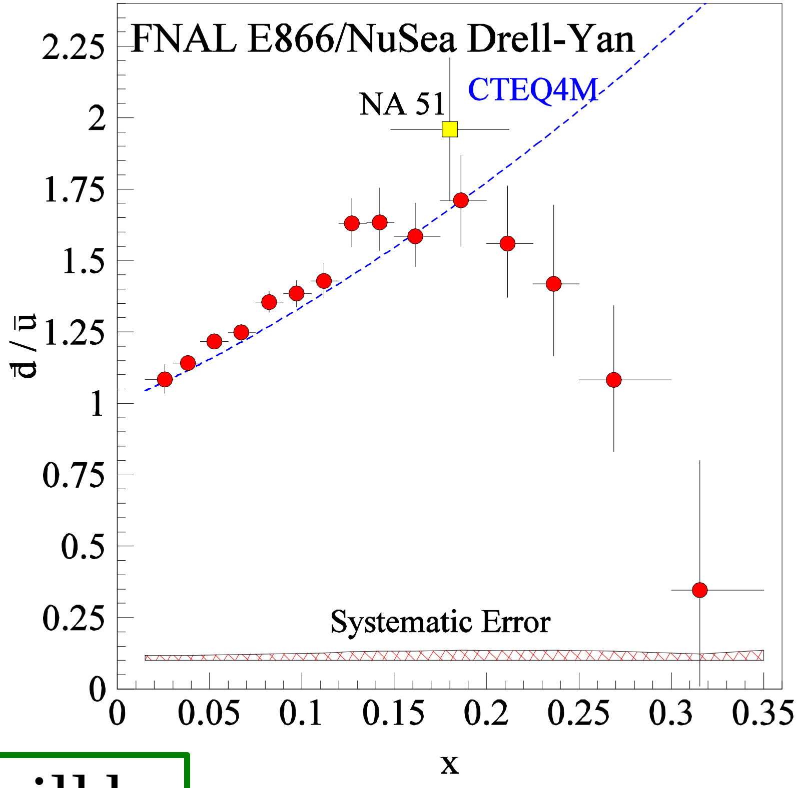
$$A_{20} = \int_0^1 x[u(x) - d(x) + \bar{u}(x) - \bar{d}(x)]dx$$

$A_{20} \sim 0.20$ from lattice QCD; $A_{20} \sim 0.15$ from data

$u(x) - d(x)$ is well known

$\bar{u}(x) - \bar{d}(x)$ is less well known

(especially at $x > 0.25$)



The apparent discrepancy in A_{20} will be reduced if $\bar{d}(x) - \bar{u}(x) < 0$ at large x

(K. Liu, JCP, W. Chang, H. Cheng, preprint)

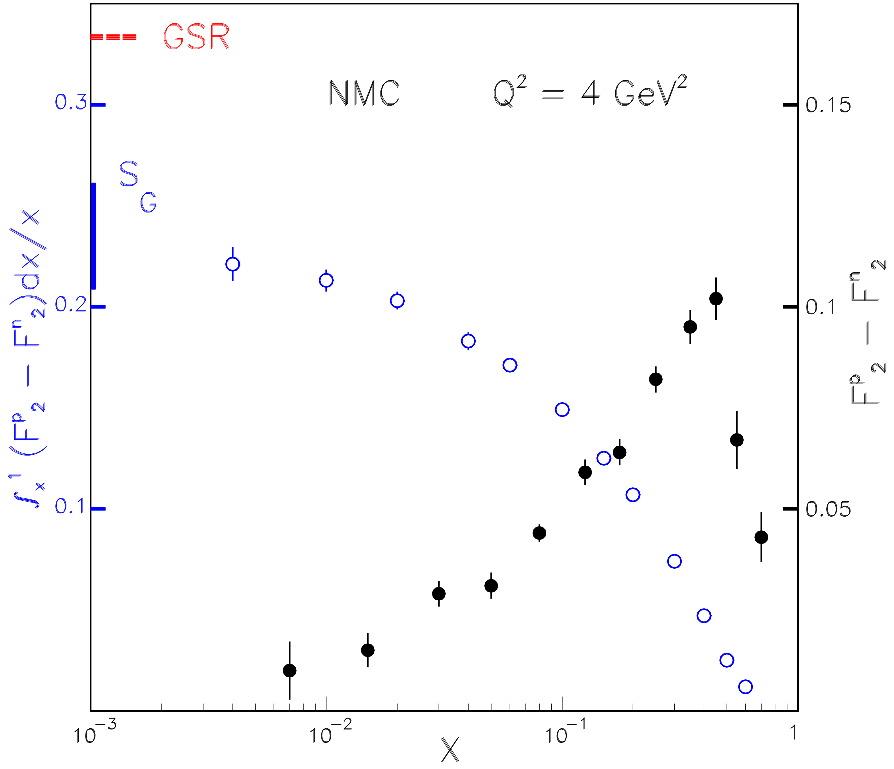
Revisit the NMC measurement of the Gottfried Sum rule

The Gottfried Sum Rule

$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\ dx$$

$$= \frac{1}{3} \qquad (if\ \bar{u}_p = \bar{d}_p)$$



New Muon Collaboration (NMC) obtains

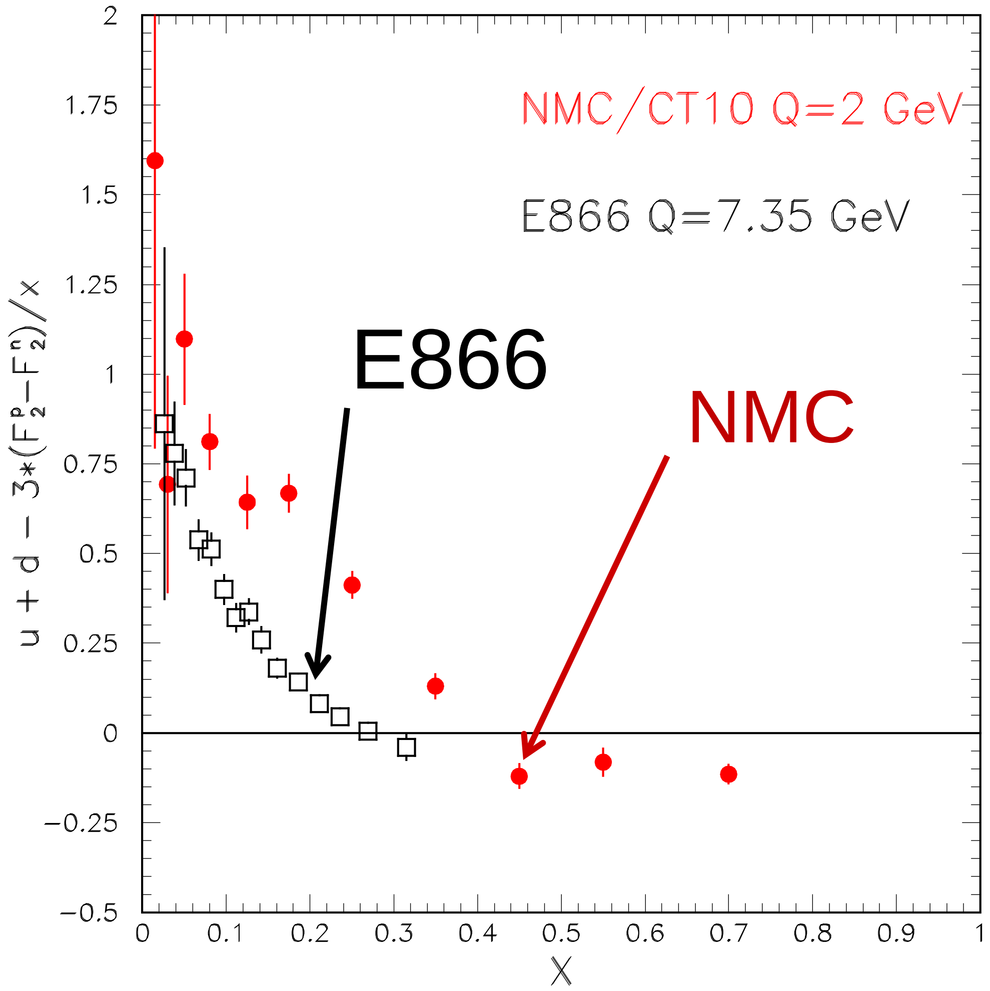
S_G = 0.235 ± 0.026

(Significantly lower than 1/3 !)

$$\Rightarrow \bar{d} \neq \bar{u}\,?$$

Extracting $\bar{d}(x) - \bar{u}(x)$ from the NMC data

$$\bar{d}(x) - \bar{u}(x) = [u(x) + d(x)]_{CT10} - 3 * [F_2^p(x)/x - F_2^n(x)/x]_{NMC}$$

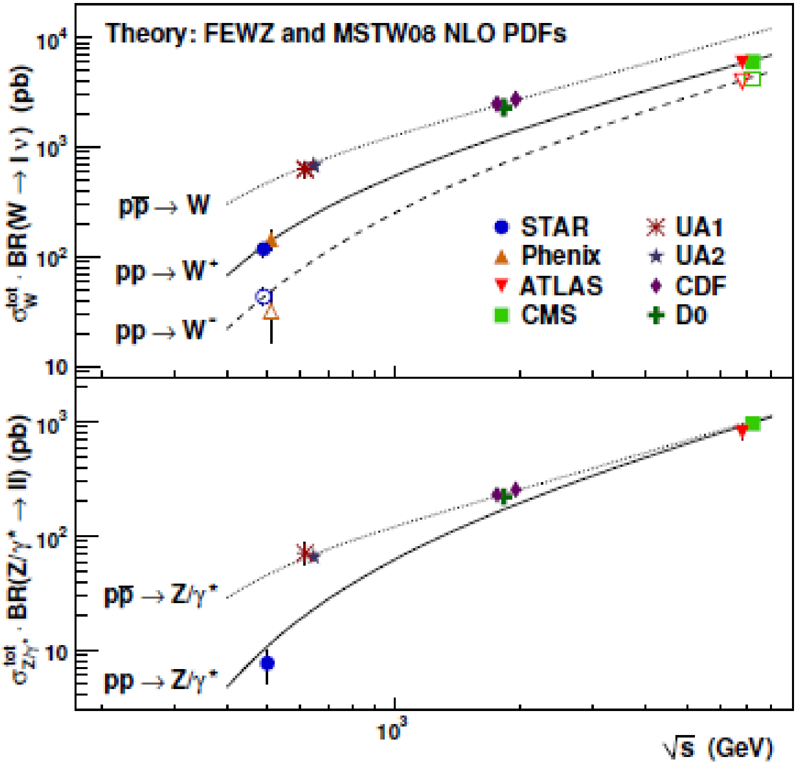


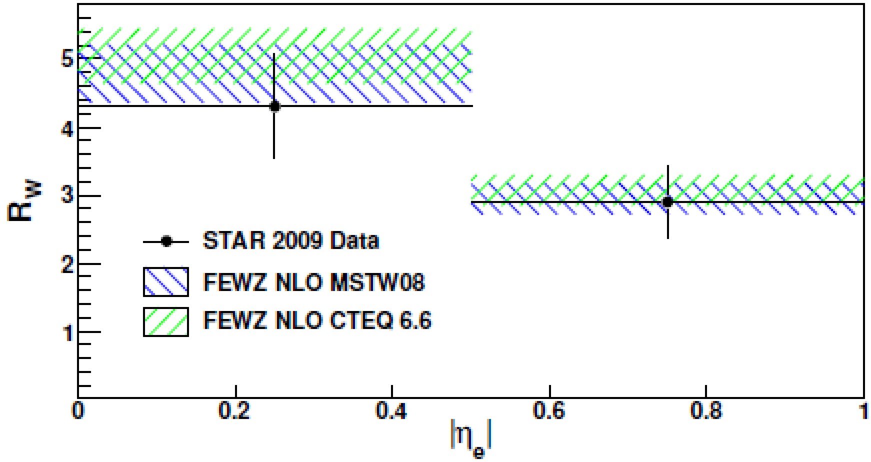
The NMC data, together with the recent PDF, already suggest that $\bar{d}(x) - \bar{u}(x) < 0$ at large x!

$\bar{d}/\bar{u}$ from W production at RHIC

$$R(x_F)=\frac{d\sigma/dx_F(pp\rightarrow W^{+}x)}{d\sigma/dx_F(pp\rightarrow W^{-}x)}\quad \text{at } \sqrt{s}=500\ \text{GeV}$$

$$R(x_F=0)\approx\frac{u(x=0.16)}{d(x=0.16)}\,\frac{\bar{d}(x=0.16)}{\bar{u}(x=0.16)}\approx 2\,\frac{\bar{d}(x=0.16)}{\bar{u}(x=0.16)}$$





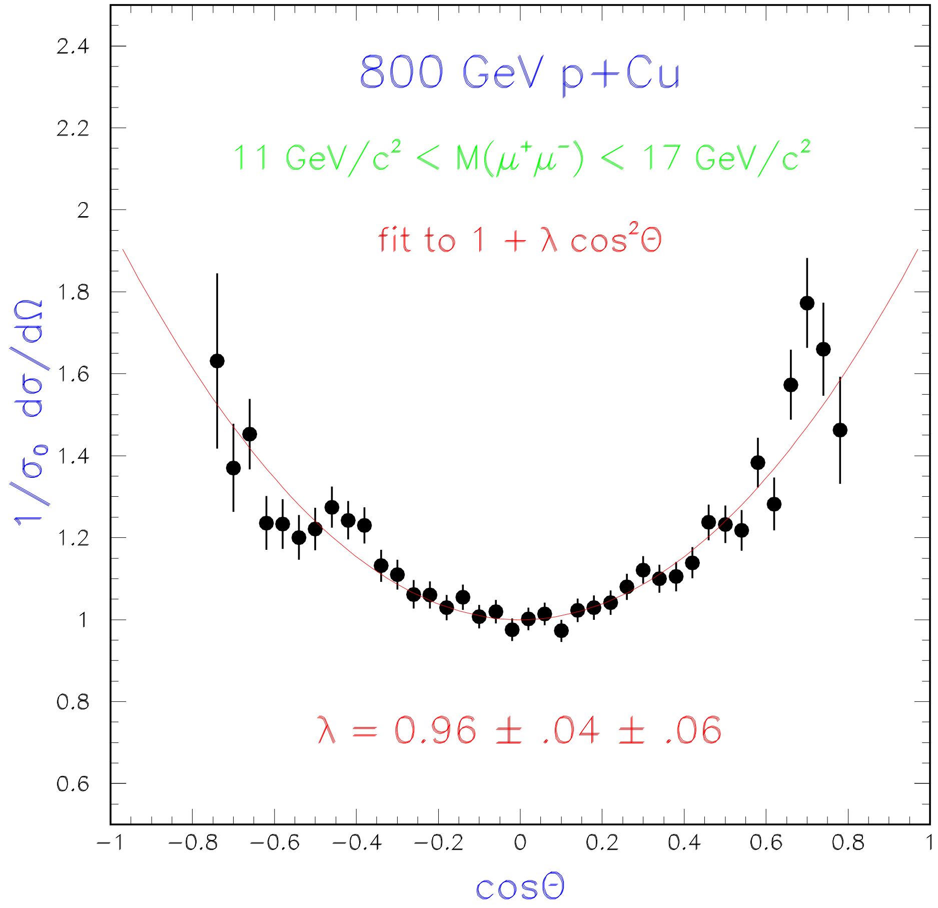
STAR: arXiv: 1112.2980

Confirms $\bar{d}/\bar{u}$ asymmetry at $x\sim 0.15$

Drell-Yan angular distribution

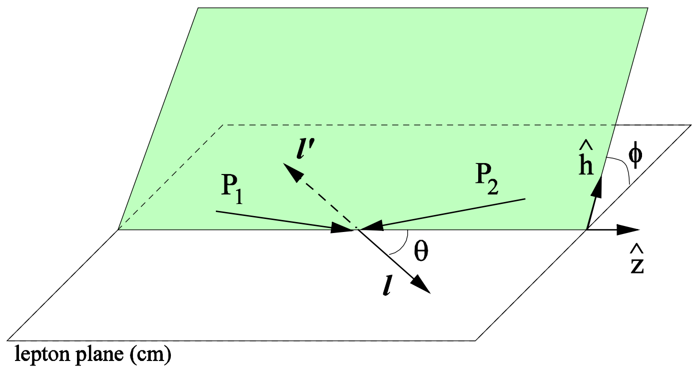
Decay Angular Distribution of “naïve” Drell-Yan:

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2 \theta)$$



Data from Fermilab E772

Drell-Yan decay angular distributions



Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

λ can differ from 1, but should satisfy $1-\lambda=2\nu$ (Lam-Tung)

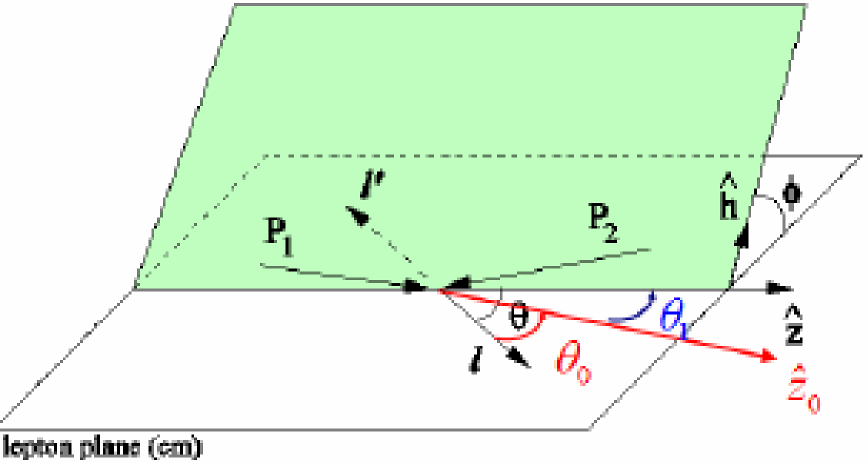
– Reflect the spin-1/2 nature of quarks

(analog of the Callan-Gross relation in DIS)

– Insensitive to QCD - corrections

A simple geometric derivation of the generalized Lam-Tung relation (a la Oleg Teryaev)

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



In the γ^* rest frame:

$\hat{z}$ signifies the Collins-Soper frame

$\hat{z}_0$ is along the collinear $q-\overline{q}$ axis

Leptons are emitted with uniform azimuthal distribution, and with θ_0 dependence:

$d\sigma \sim 1+\lambda_0\cos^2\theta_0$

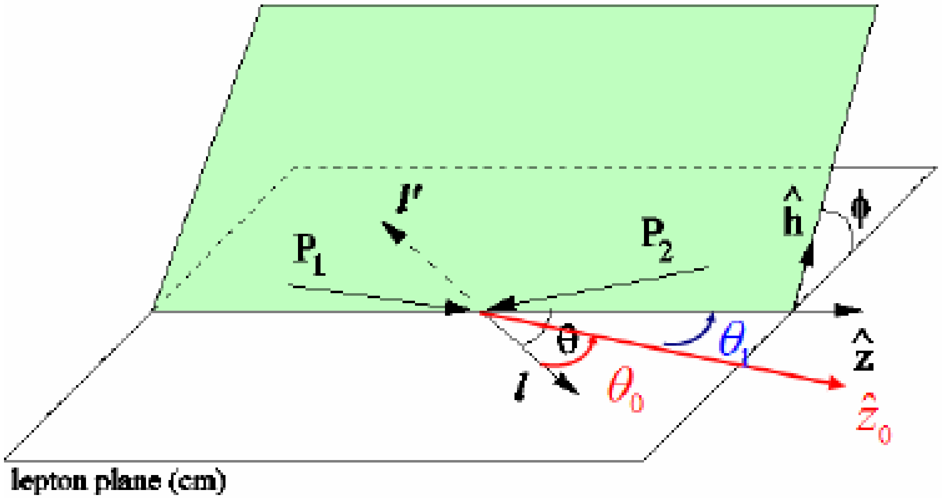
($\lambda_0 = 1$ for spin-1/2 quark;
$\lambda_0 = -1$ for spin-0 quark)

$$\cos\theta_0 = \cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi$$

$$\begin{aligned} d\sigma &\sim 1+\lambda_0(\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi)^2 \\ &= [1+(\lambda_0/2)\sin^2\theta_1]+\cos^2\theta[\lambda_0\cos^2\theta_1-(\lambda_0/2)\sin^2\theta_1] \\ &\quad +\sin 2\theta\cos\phi[(\lambda_0/2)\sin 2\theta_1]+\sin^2\theta\cos 2\phi[(\lambda_0/2)\sin^2\theta_1] \end{aligned}$$

A simple geometric derivation of the generalized Lam-Tung relation (a la Oleg Teryaev)

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



Therefore, we have

$$\lambda=\lambda_0\frac{2\text{-}3\sin^2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

$$\mu=\lambda_0\frac{\sin 2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

$$\nu=\lambda_0\frac{2\sin^2\theta_1}{2+\lambda_0\sin^2\theta_1}$$

and

$$\lambda_0=\frac{\lambda+\frac{3}{2}\nu}{1-\frac{1}{2}\nu}$$ (Generalized Lam-Tung relation)

If $\lambda_0=1$, we have $2\nu=1\text{-}\lambda$ (Lam-Tung relation)

If $\lambda_0=\text{-}1$ (spin-0 quark), we have $\text{-}\nu=1+\lambda$

$$d\sigma\sim 1+\lambda_0(\cos\theta\cos\theta_1+\sin\theta\sin\theta_1\cos\phi)^2$$

$$=[1+(\lambda_0/2)\sin^2\theta_1]+\cos^2\theta[\lambda_0\cos^2\theta_1-(\lambda_0/2)\sin^2\theta_1]$$

$$+\sin 2\theta\cos\phi[(\lambda_0/2)\sin 2\theta_1]+\sin^2\theta\cos 2\phi[(\lambda_0/2)\sin^2\theta_1]$$

Decay angular distributions in pion-induced Drell-Yan

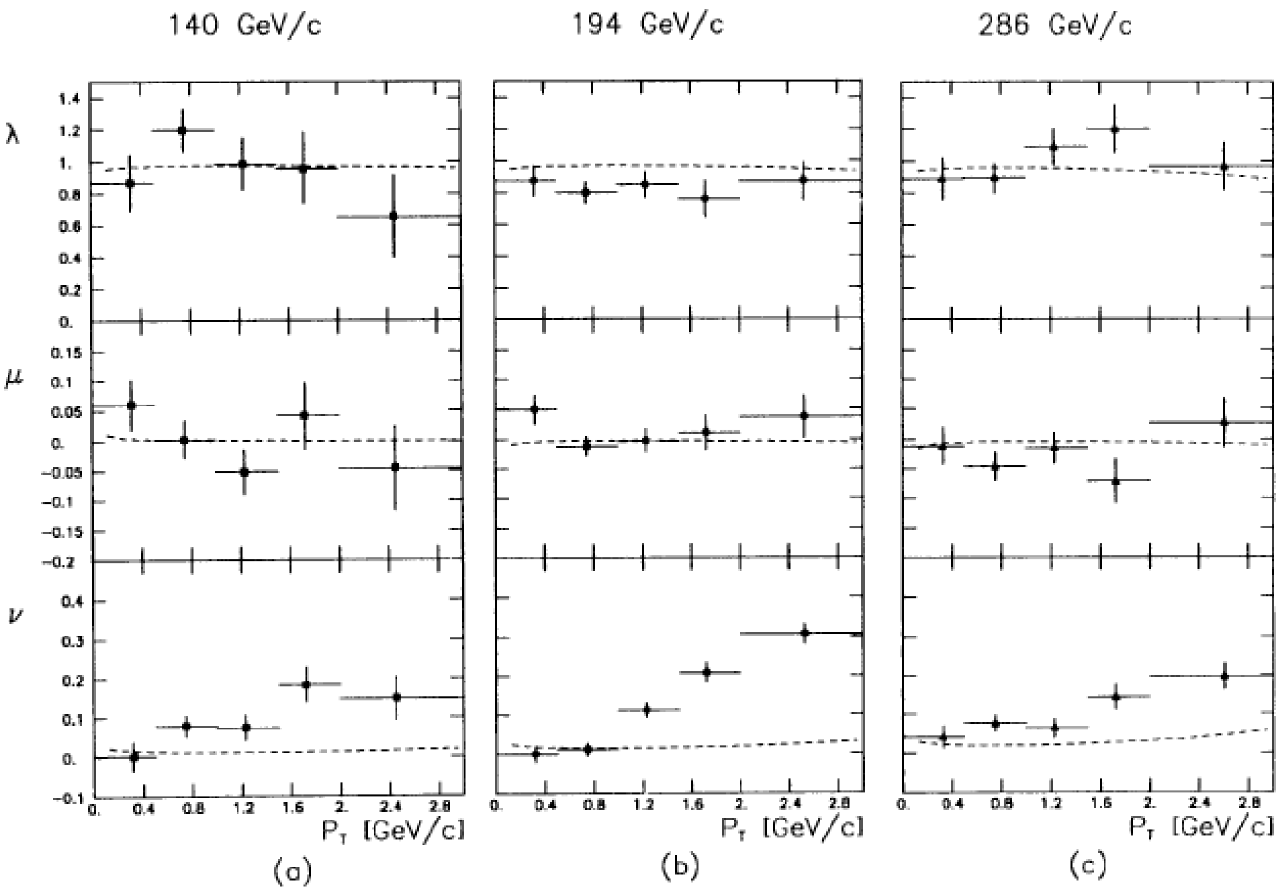


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + \mathbf{W}$

Z. Phys.

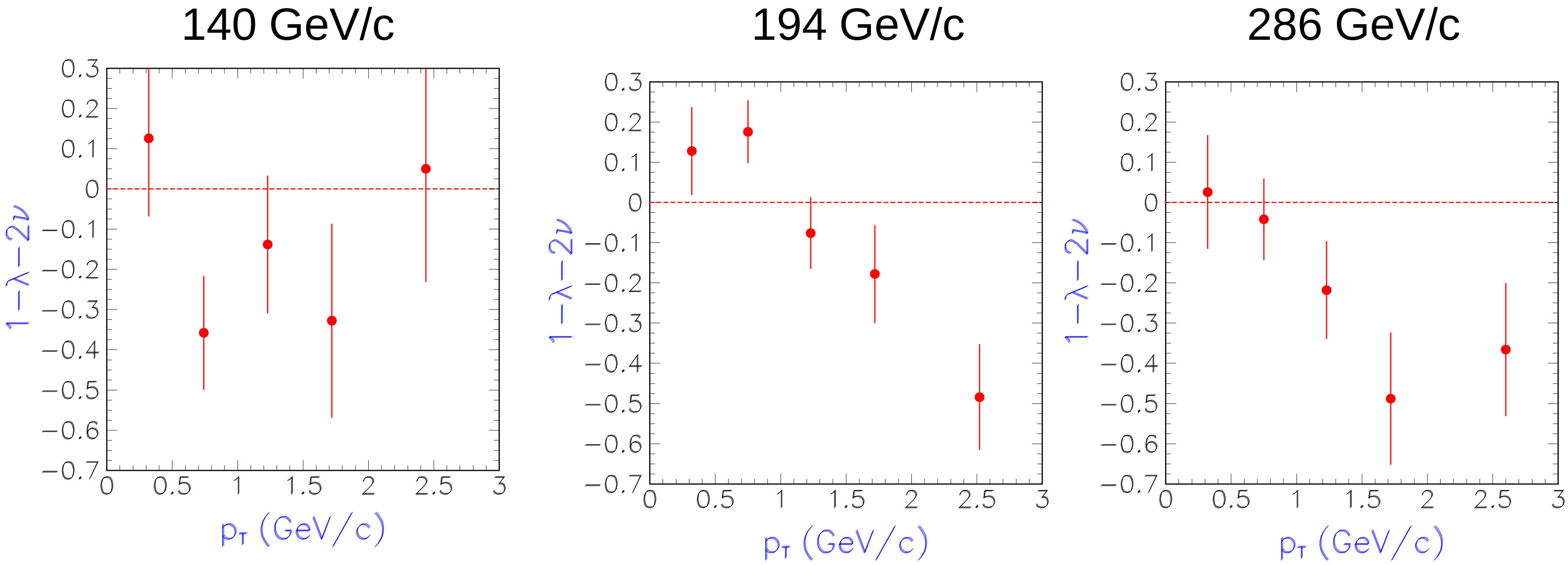
37 (1988) 545

Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

Decay angular distributions in pion-induced Drell-Yan

Is the Lam-Tung relation violated?



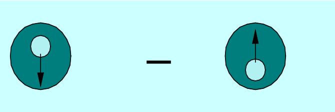
Data from NA10 (Z. Phys. 37 (1988) 545)

Violation of the Lam-Tung relation suggests

new mechanisms with non-perturbative origin

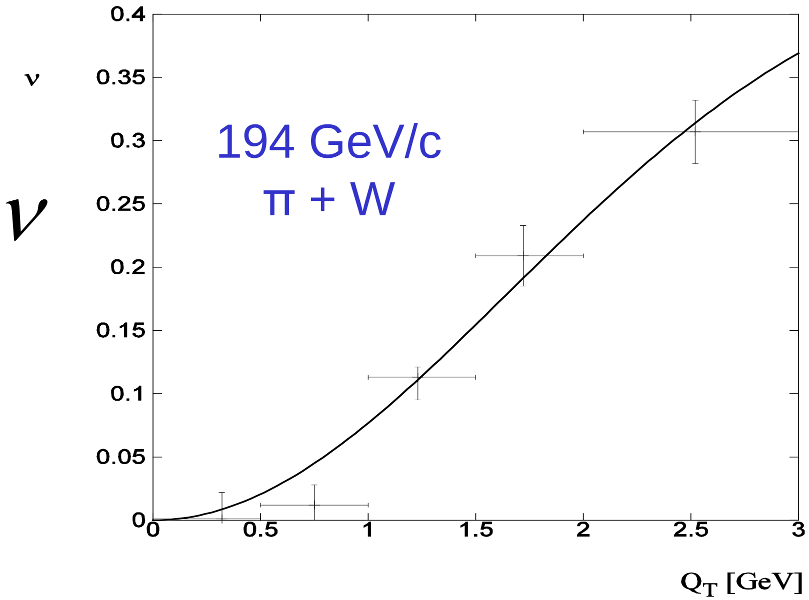
- $q-\overline{q}$ spin correlation in QCD color field (Nachtmann et al.)

Boer-Mulders function $h_1^\perp$



- $h_1^\perp$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron
- $h_1^\perp$ is a time-reversal odd, chiral-odd TMD parton distribution
- $h_1^\perp$ can lead to an azimuthal cos(2ϕ) dependence in Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



Boer, PRD 60 (1999) 014012

- Observation of large cos(2Φ) dependence in Drell-Yan with pion beam
- $\nu \propto h_1^\perp(x_q)h_1^\perp(x_{\bar{q}})$
- B-M functions have same signs for pion and nucleon

Three parton distributions describing quark's transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

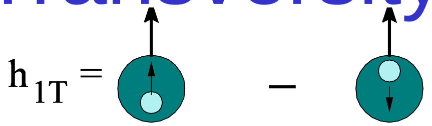
$\vec{s}_\perp^q$

3) Qaurk transverse momentum

$\vec{k}_\perp^q$

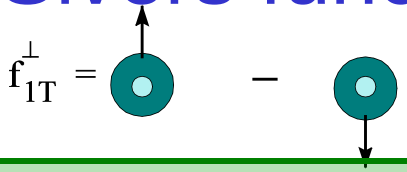
⇒ Three different correlations

1) Transversity



Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function



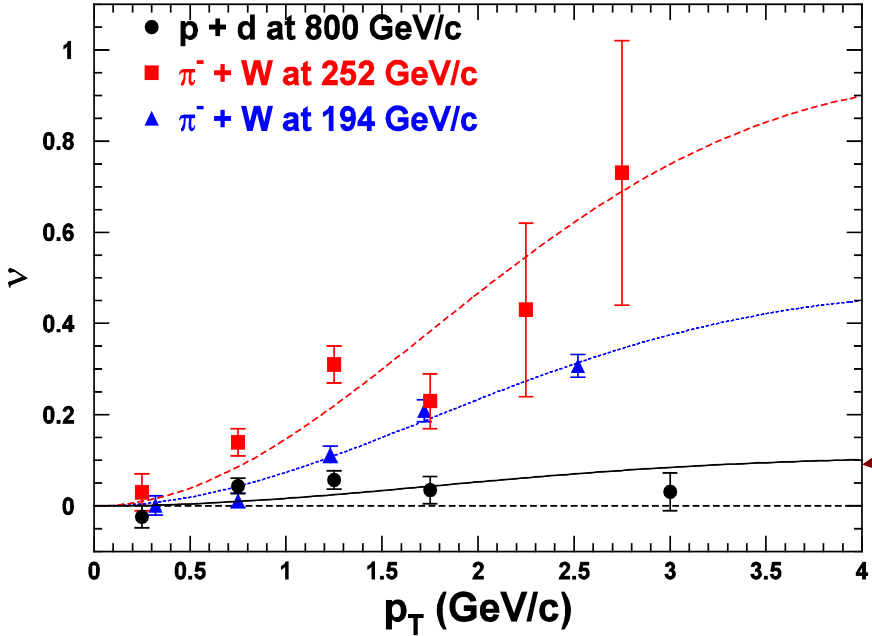
Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

Azimuthal cos2Φ Distribution in p+p and p+d Drell-Yan

E866 Collab., Lingyan Zhu et al.,
PRL 99 (2007) 082301; PRL 102 (2009) 182001



Small ν is observed for p+d and p+p D-Y

With Boer-Mulders function $h_1^\perp$:

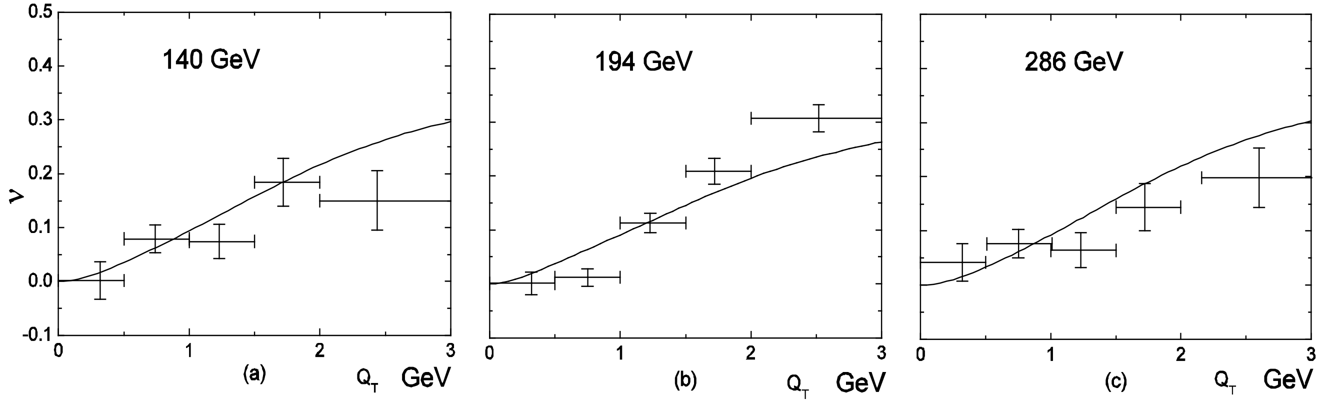
$\nu(\pi^- W \rightarrow \mu^+\mu^- X)$~ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \rightarrow \mu^+\mu^- X)$~ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Sea-quark BM functions are much smaller than valence quarks

Sea-quark Boer-Mulders Functions

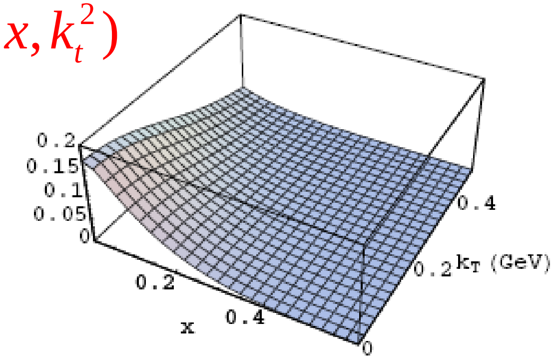
1) Use quark-spectator-antiquark model to calculate pion B-M functions. Pion-induced Drell-Yan data are well reproduced.



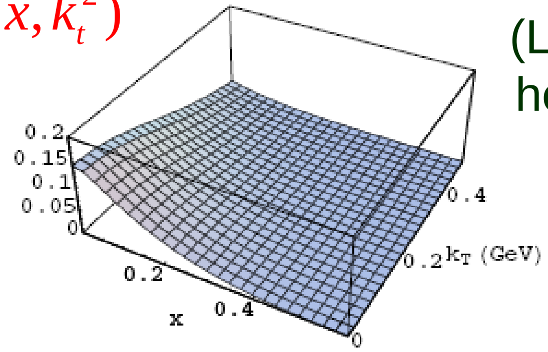
(Lu and Ma, hep-ph/0504184)

2) Use pion-cloud model convoluted with the pion B-M function to calculate sea-quark B-M for proton.

$h_1^{\perp,\bar{u}}(x,k_t^2)$



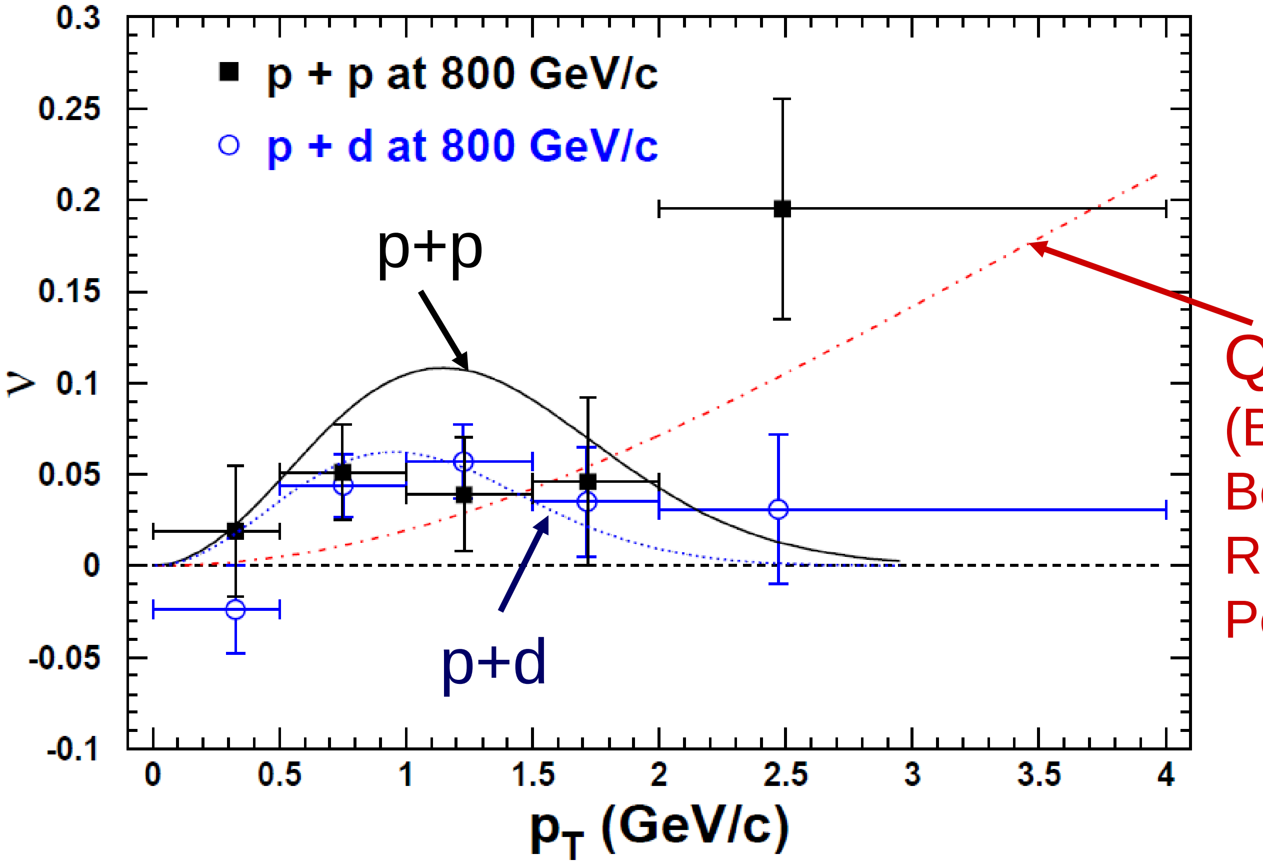
$h_1^{\perp,\bar{d}}(x,k_t^2)$



(Lu, Ma, Schmidt, hep-ph/0701255)

Results on cos2Φ Distribution in p+p Drell-Yan

L. Zhu et al., PRL 102 (2009) 182001

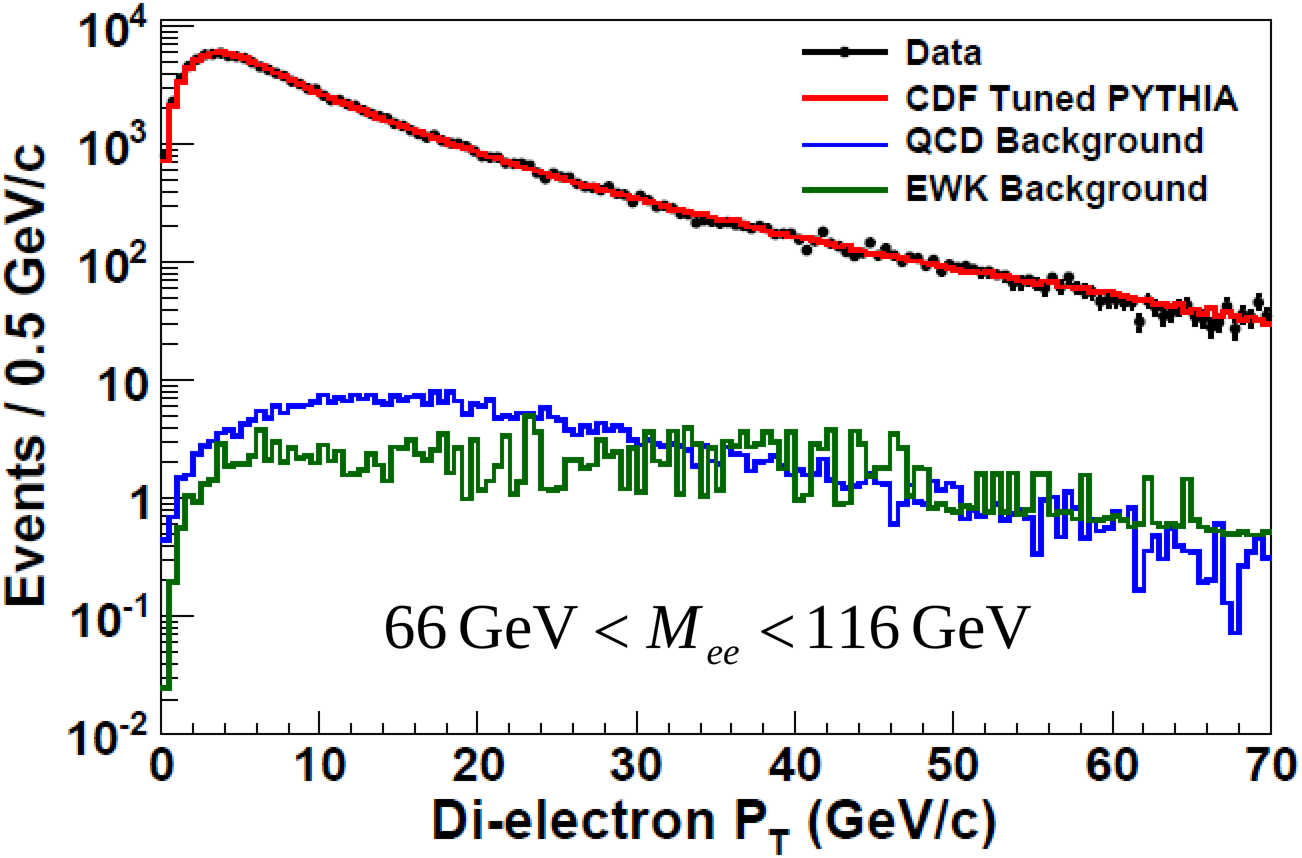


QCD
(Boer, Vogelsang;
Berger, Qiu,
Rodriguez-
Pedraza)

More data are anticipated from Fermilab E906 and COMPASS

Recent result from CDF on Lam-Tung relation

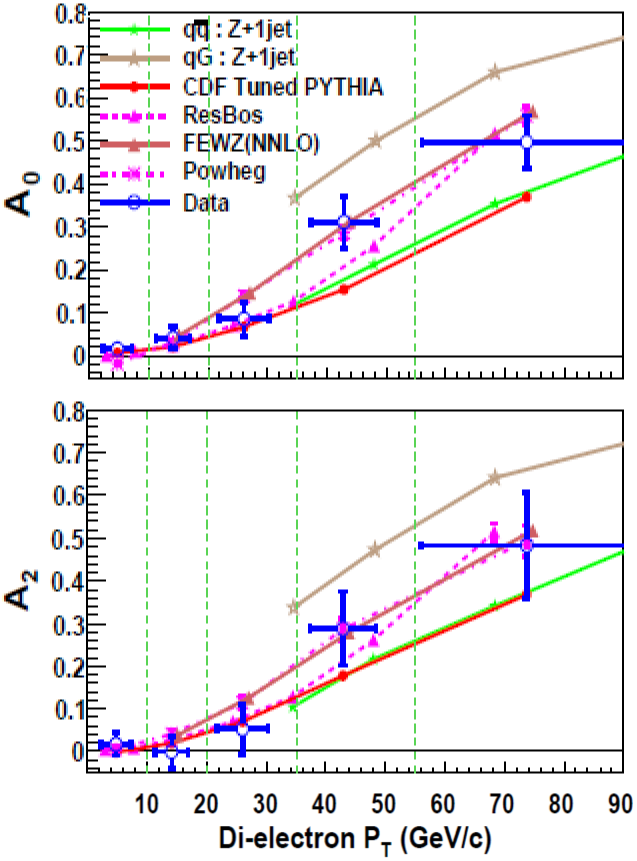
$$p + \bar{p} \rightarrow e^{+} + e^{-} + X \quad \text{at} \sqrt{s} = 1.96\,\text{TeV}$$



arXiv:1103.5699

Recent result from CDF on Lam-Tung relation

$$p + \overline{p} \rightarrow e^{+} + e^{-} + X \ \text{ at } \sqrt{s} = 1.96\,\text{TeV}$$



$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

$$\frac{d\sigma}{d\phi} \propto 1 + \beta_3\cos\phi + \beta_2\cos 2\phi + \beta_7\sin\phi + \beta_5\sin 2\phi$$

$$\beta_3 = 3\pi A_3/16,\ \beta_2 = A_2/4,\ \beta_7 = 3\pi A_7/16$$

$$\text{Lam - Tung relation} \Rightarrow A_0 = A_2$$

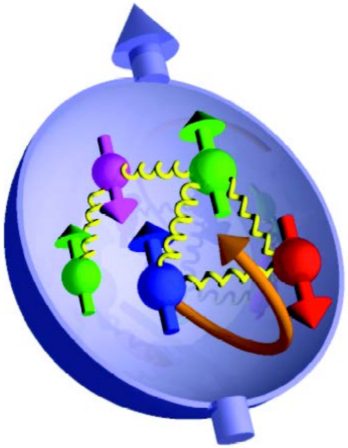
P_T bin	A_0 $(\times 10^{-1})$	A_2 $(\times 10^{-1})$
0–10	$0.17 \pm 0.14 \pm 0.07$	$0.16 \pm 0.26 \pm 0.06$
10–20	$0.42 \pm 0.25 \pm 0.07$	$-0.01 \pm 0.35 \pm 0.16$
20–35	$0.86 \pm 0.39 \pm 0.08$	$0.52 \pm 0.51 \pm 0.29$
35–55	$3.11 \pm 0.59 \pm 0.10$	$2.88 \pm 0.84 \pm 0.19$
> 55	$4.97 \pm 0.61 \pm 0.10$	$4.83 \pm 1.24 \pm 0.02$

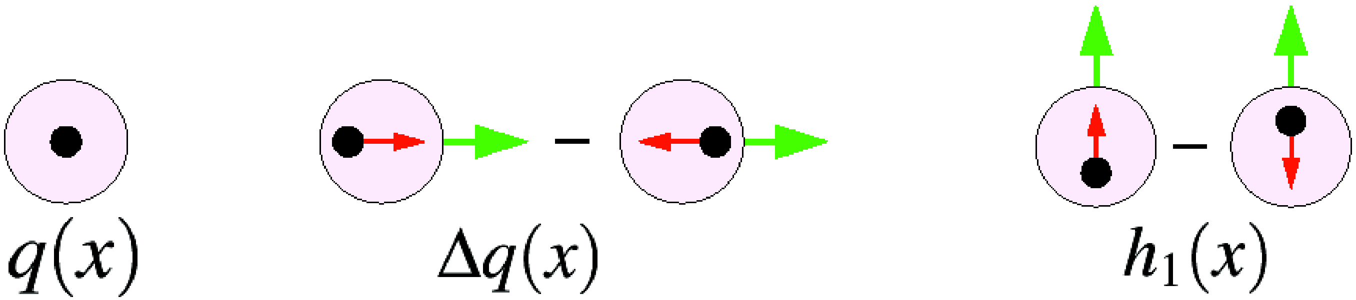
arXiv:1103.5699

$$\langle A_0 - A_2 \rangle = 0.02 \pm 0.02$$

Polarized Drell-Yan with polarized proton beam?

- Polarized Drell-Yan experiments have never been done before
- Provide unique information on the quark (antiquark) spin





Quark helicity distribution

Quark transversity distribution

Transversity and Transverse Momentum Dependent PDFs are also probed in Drell-Yan

a) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$

b) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$$

c) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$$

- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

Outstanding questions to be addressed by future Drell-Yan experiments

- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

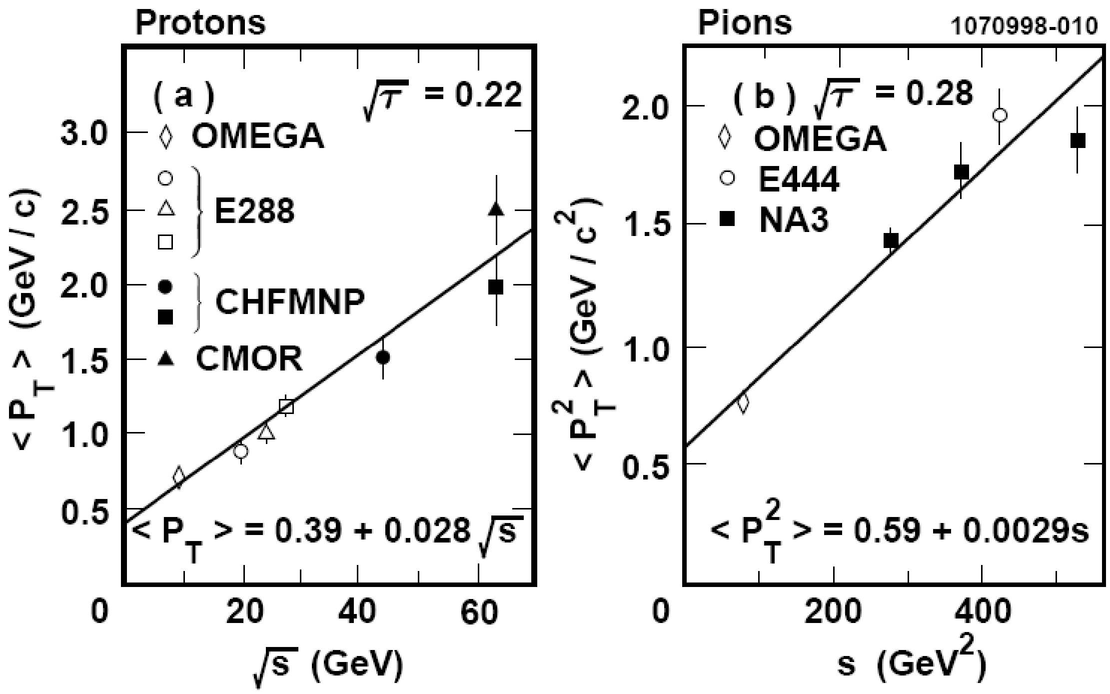
Can be studied at COMPASS, RHIC, FAIR, JPARC, JINR, etc

What do we know about the quark and gluon intrinsic transverse momentum distributions?

- Does the quark $\mathrm{k_T}$ distribution depend on *x*?
- Do valence quarks and sea quarks have different k_T distributions?
- Do *u* and *d* quarks have the same k_T distribution?
- Do nucleons and mesons have different quark k_T distribution?
- Do gluons have k_T distribution different from quarks?

- Important for extracting the TMD parton distributions
- Interesting physics in its own right

What do Drell-Yan data tell us about the quark intrinsic transverse momentum distribution?



- $<P_T^2>$ increases linearly with s (expected from QCD)
- Proton-induced D-Y has smaller mean P_T than pion (expected from the uncertainty principle, reflecting the larger size of the proton)

Comparison of the mean P_T of proton, pion, and kaon induced Drell-Yan

Drell-Yan with proton beam:

$$\langle P_T \rangle = (0.43 \pm 0.03) + \sqrt{s}(0.026 \pm 0.001)\ \text{GeV/c}$$

Drell-Yan with pion beam:

$$\langle P_T \rangle = (0.59 \pm 0.05) + \sqrt{s}(0.028 \pm 0.003)\ \text{GeV/c}$$

NA3 data also show that $\langle P_T \rangle$ for D-Y with kaon beam is larger than Drell-Yan with pion beam:

$$\langle P_T{}^2 \rangle = 1.51 \pm 0.08\,(\text{GeV/c})^2 \ \text{ for kaon beam}$$

$$\langle P_T{}^2 \rangle = 1.44 \pm 0.02\,(\text{GeV/c})^2 \ \text{ for pion beam}$$

with 150 GeV/c beams

New Drell-Yan data with meson and antiproton beams are essential

The data suggest:

$$\langle k_T \rangle_{kaon} > \langle k_T \rangle_{pion} > \langle k_T \rangle_{proton}$$

We know

$$\langle r \rangle^{1/2}{}_{kaon} < \langle r \rangle^{1/2}{}_{pion} < \langle r \rangle^{1/2}{}_{proton}$$

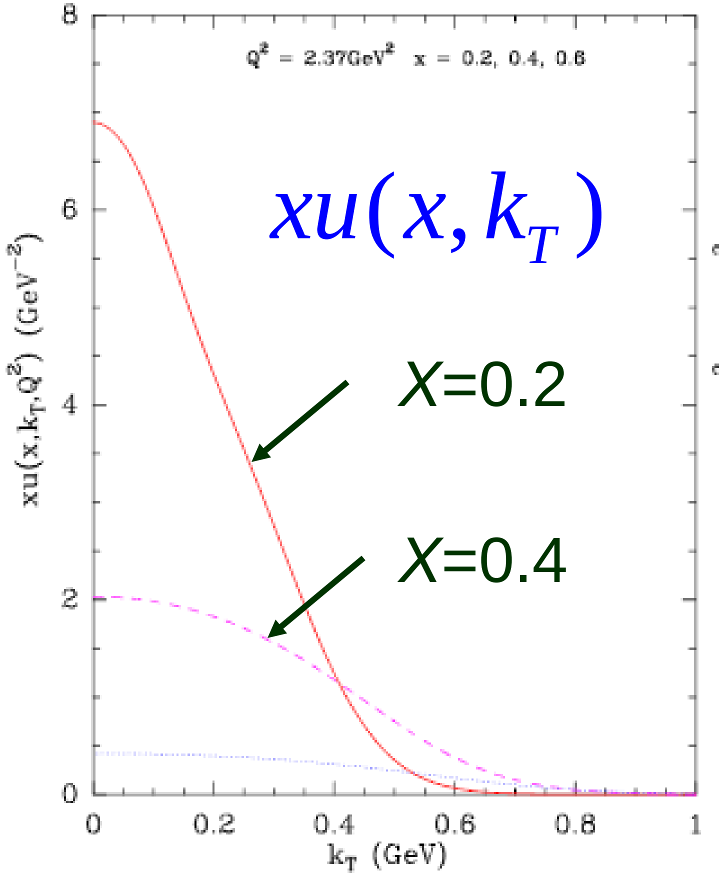
$$\langle r \rangle^{1/2} = 0.58 \pm 0.02\text{fm for kaon}$$

$$\langle r \rangle^{1/2} = 0.67 \pm 0.02\text{fm for pion}$$

$$\langle r \rangle^{1/2} = 0.81\text{fm for proton}$$

Flavor and *x*-dependent k_T-distributions?

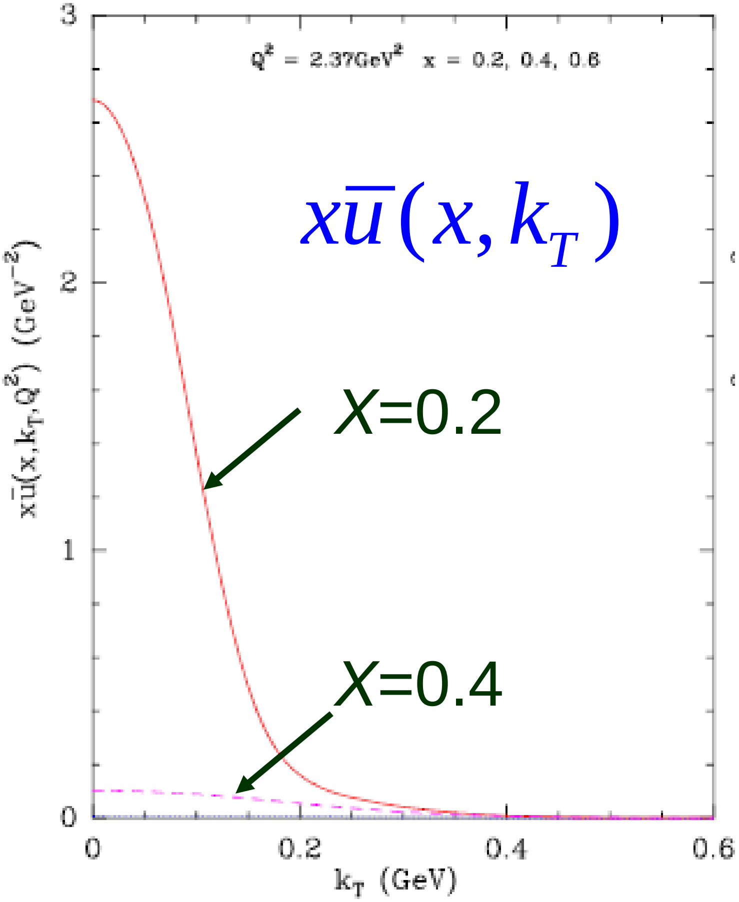
(Bourrely, Buccella, Soffer, arXiv:1008.5322)



$xu(x,k_T)$

X=0.2

X=0.4



$x\bar{u}(x,k_T)$

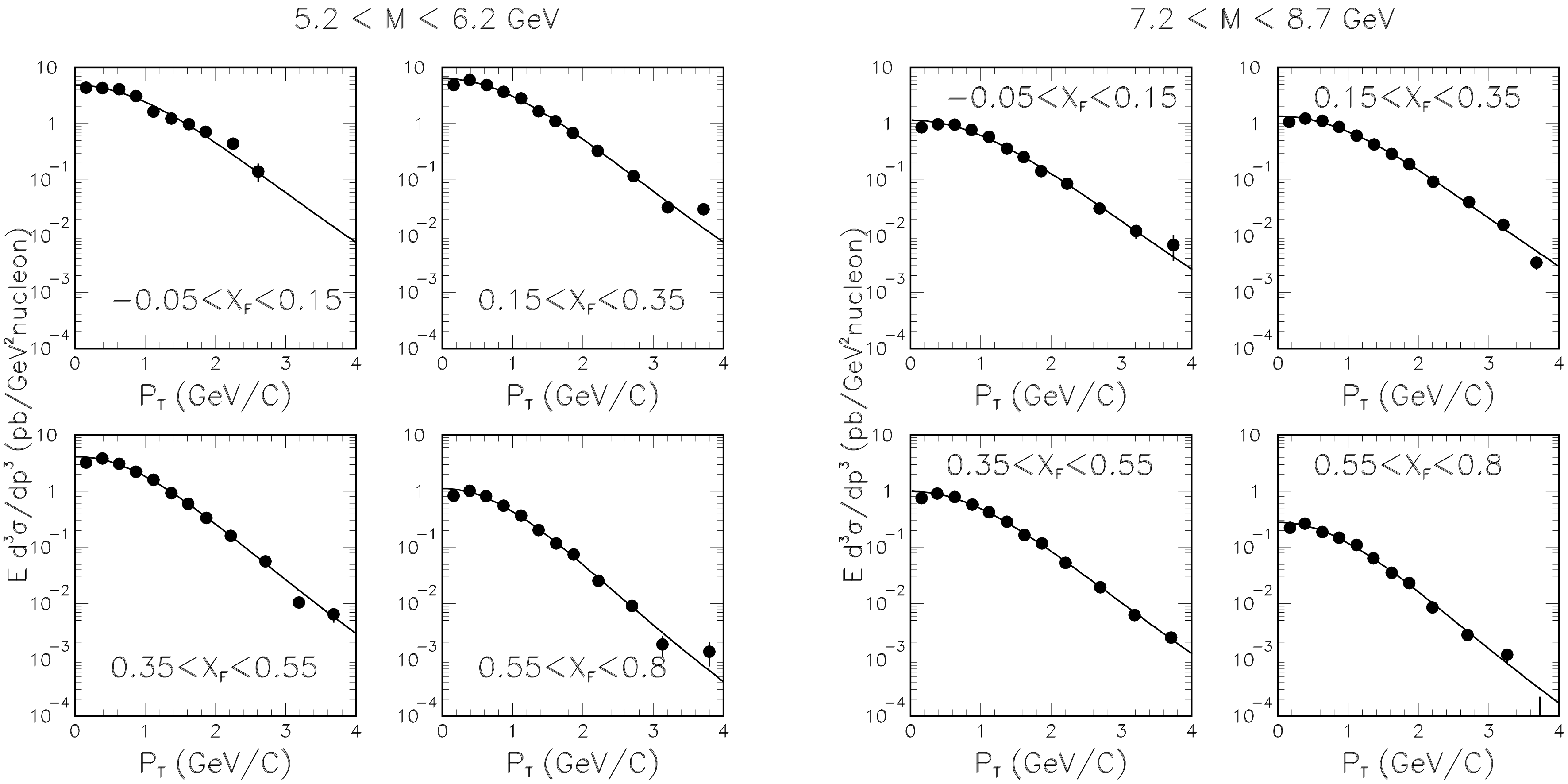
X=0.2

X=0.4

- $\langle k_T \rangle$ increases when x increases
- $\langle k_T \rangle$ for sea quarks is smaller than for valence quarks

Test of possible *x*-dependent k_T-distributions

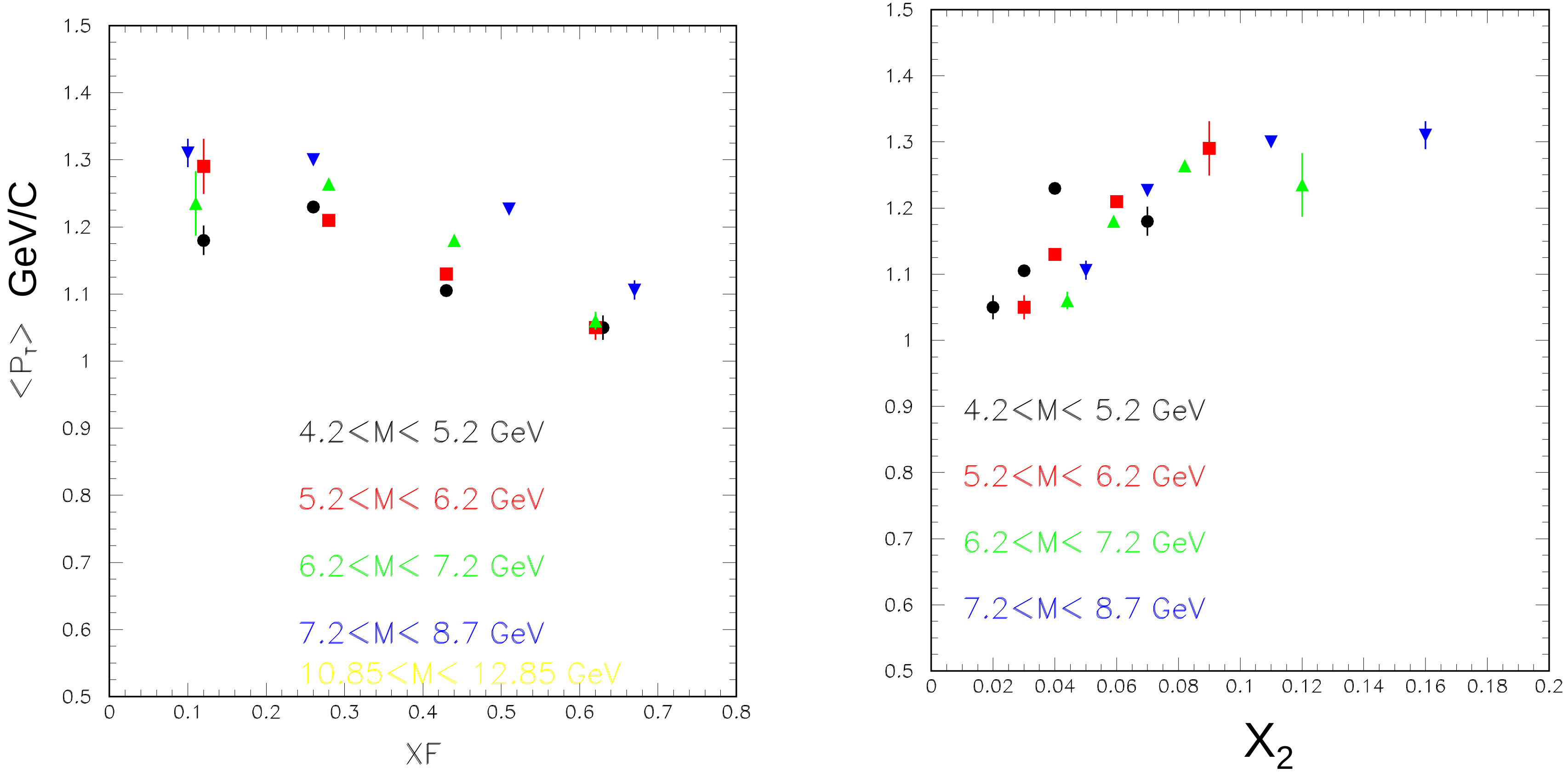
E866 p+d D-Y data (800 GeV beam)



Data from thesis of J. Webb

Possible *x*-dependent k_T-distributions

E866 p+d D-Y data (800 GeV beam)



$\langle p_T \rangle$ scale with x_2 ?

Analysis is ongoing (A. Ghalsasi, E. McClellan,JCP)

Summary

- The Drell-Yan process is a powerful experimental tool complimentary to the DIS for exploring quark structures in nucleons and nuclei.

- Unique information on flavor structures of sea-quark has been obtained with Drell-Yan experiments. First results on TMD have also been extracted.

- Future Drell-Yan experiments can address many important unresolved issues in the spin and flavor structures of nucleons and nuclei.